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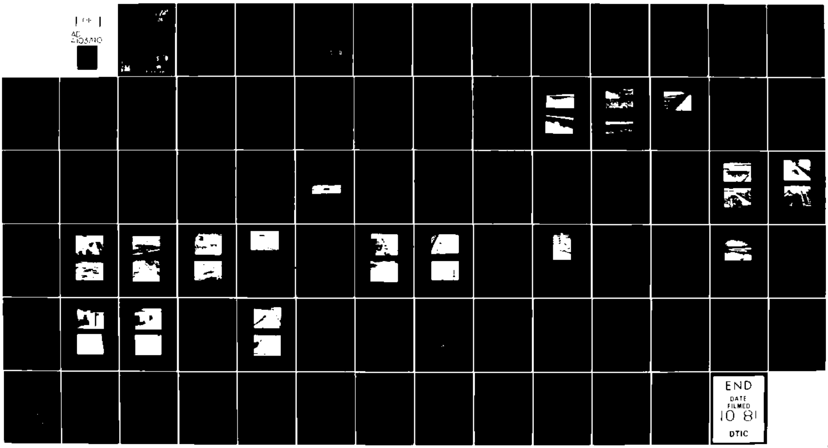

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THE EFFECTS OF ICE ON COAL MOVEMENT VIA THE INLAND WATERWAYS

V.J. Lunardini, L.D. Minsk and G. Phetteplace

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The Inland Waterways now carry about 11% of the coal production of the United States. Significant increases in the production, use, and transportation of coal have been projected. The ability of the Inland Waterways to increase its coal handling capacity, especially during the winter has been questioned. That part of the Inland Waterways which carries significant coal and which may experience significant ice problems includes the following rivers or waterways: Ohio, Monongahela, Allegheny, Kanawha, Upper Mississippi, and Illinois. Coal transportation along these rivers may be locally interrupted for periods up to

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20. Abstract (cont'd)

30 days or more every three to five years. Coal handling facilities, navigation channels, and lock and dam sites along the ice prone rivers were surveyed by visit or telephone to ascertain the scope of the ice problems. Coal moves through any part of the waterways system as a series flow from the coal loading/unloading facilities, along the navigation channels and through the locks to its destination. The importance of ice as a barrier to increased coal movement on the waterways studied manifests itself differently for each link of the flow system. In order of importance the ice will affect the navigation channels, locks and dams, and finally the coal loading/unloading facilities. The coal handling facilities will not be significantly slowed down by ice problems associated with winter navigation. Only rarely is a coal handling facility stopped by ice when the locks and dams or navigation channels are operating normally. The major exception may be the rail car to barge loading link which can cause slowdowns due to coal freezing in the rail cars.

Preface

This report was prepared by Dr. Virgil Lunardini, Jr., Mechanical Engineer; L. David Minsk, Research Physical Scientist; and Gary E. Phetteplace, Mechanical Engineer. The authors are members of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The study was performed for the Department of Energy under Contract DE-A101-80ET14356.

The report was technically reviewed by Dr. George D. Ashton, Arnold M. Dean, Jr., Stephen L. DenHartog, and Guenther E. Frankenstein of CRREL.

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Summary

The Inland Waterways now carry about 11% of the coal production of the United States. Significant increases in the production, use, and transportation of coal have been projected. The ability of the Inland Waterways to increase its coal handling capacity, especially during the winter has been questioned. That part of the Inland Waterways which carries significant coal and which may experience significant ice problems includes the following rivers or waterways: Ohio, Monongahela, Allegheny, Kanawha, Upper Mississippi, and Illinois. Coal transportation along these rivers may be locally interrupted for periods up to 30 days or more every three to five years. Coal handling facilities, navigation channels, and lock and dam sites along the ice prone rivers were surveyed by visit or telephone to ascertain the scope of the ice problems. Coal moves through any part of the waterways system as a series flow from the coal loading/unloading facilities, along the navigation channels and through the locks to its destination. The importance of ice as a barrier to increased coal movement on the waterways studied manifests itself differently for each link of the flow system. In order of importance the ice will affect the navigation channels, locks and dams, and finally the coal loading/unloading facilities. The coal handling facilities will not be significantly slowed down by ice problems associated with winter navigation. Only rarely is a coal handling facility stopped by ice when the locks and dams or navigation channels are operating normally. The major exception may be the rail car to barge loading link which can cause slowdowns due to coal freezing in the rail cars.

Further research and development are recommended into the:

a) effect of navigation on ice in navigation channels;
b) prevention of ice formation in navigation channels;
c) removal or storage of channel ice;
d) use of thermal energy for ice control at locks and dams;
e) lock and dam design modifications for ice operation;
f) coal/ice bond and its effect upon transfer of coal from trains to river tows;
g) effect of winter navigation on coal storage requirements.

Winter movement of coal along the ice prone waterways exacts an economic penalty but it was not possible to quantify this cost.

INTRODUCTION

Coal use in the western world is expected to double by 1990 and triple by 2000, according to the World Coal Study (1)[1]. The World Coal Study projects a demand, by the year 2000, for 1 billion tons of steam coal per year by the 16 participating countries, which together consume 75% of the world's energy and 60% of the world's coal. In the United States, in 1975 about 65 million tons of coal moved by water and another 10 million tons were shipped by rail/water (2). By 1990 the National Energy Transportation Study (3) projects water movement of 105 million tons and rail/water movement of an additional 41-77 million tons.

This increased tonnage will put demands on the waterways shipping system which may require routine operation during the winter. Currently the Upper Mississippi River (above Burlington, IA) is closed to traffic during most of the winter because of the presence of ice. During the winter, only limited traffic moves on the upper Monongahela River to the head of navigation near Fairmont, WV. Traffic is stopped nearly every year on the Illinois Waterway due to ice. On all portions of the system where ice is found, the capacity to move commodities is reduced during some part of the winter season.

This study examines the problems caused by ice on the movement of coal on the Inland Waterways. Only those portions of the Inland Waterways which are subject to ice and currently operate year round are considered together with the facilities for loading and unloading coal along them. The study examines the following topics:

1. Ice-prone portions of the domestic waterways system which handle coal year round.
2. Specific ice problems, present methods used to cope with ice, and state of the art ice handling techniques.
3. The effect of ice problems on the waterways system if its coal handling requirement is doubled within 10 years.
4. Critical problems which will require further research or development.

The purpose of this study is not to present solutions to specific problems but merely to ascertain the existence and extent of ice problems on the movement of coal through the Inland Waterways and, in particular, at coal handling facilities along the inland waterways system. The study was carried out by on-site and telephone surveys of various coal handling facilities along the ice prone rivers identified.

[1] Numbers in parentheses refer to references listed at the end of the report.

THE INLAND WATERWAYS SYSTEM

The inland waterways system consists of over 25,000 miles of navigable rivers and canals. Only that portion of the inland waterway system experiencing ice-caused delays or damage to fixed or floating facilities is included in this study. Excluded therefore are the Missouri River, upper Hudson River and New York State Barge Canal, all of which are closed to navigation during the winter; rivers carrying small amounts of coal are also excluded). The system comprises the following rivers with their navigable lengths:

Ohio	981 miles
Monongahela	129
Upper Mississippi (Cairo, IL to St. Paul, MN)	858
Illinois Waterway	326
Kanawha	97
Allegheny	72
Kaskaskia	36

The portion of the inland waterways of interest to this study is shown in Fig. 1.

Locks and dams are located on all these rivers. The dam, itself, regulates the depth of water for navigation and flood control. The purpose of a lock is to transfer vessels from one river level to a different level. In 1959 the Corps of Engineers (4), adopted the following standard lock dimensions:

Width (ft)	Length (ft)
66	400, 600
84	600, 800, 1200
110	600, 800, 1200

Some locks designed prior to 1959 have non-standard dimensions. A tabulation of the locks and their dimensions, for that part of the waterways included in the study, is given in Tables 1-6 (5).

The characteristics of the segments of the waterways system are:

Ohio River. The river is formed by the junction of the Allegheny and Monongahela Rivers at Pittsburgh, PA, and flows generally southwesterly for 981 miles, joining the Mississippi River at Cairo, IL. There are 20 locks and dams.

Monongahela River, West Virginia and Pennsylvania. The river is formed by the junction of the Tygart and West Fork Rivers about 1 mile south of Fairmont, WV, and flows north for 128.7 miles to its junction with the Allegheny River at Pittsburgh, PA to form the Ohio River. There are nine locks and dams.

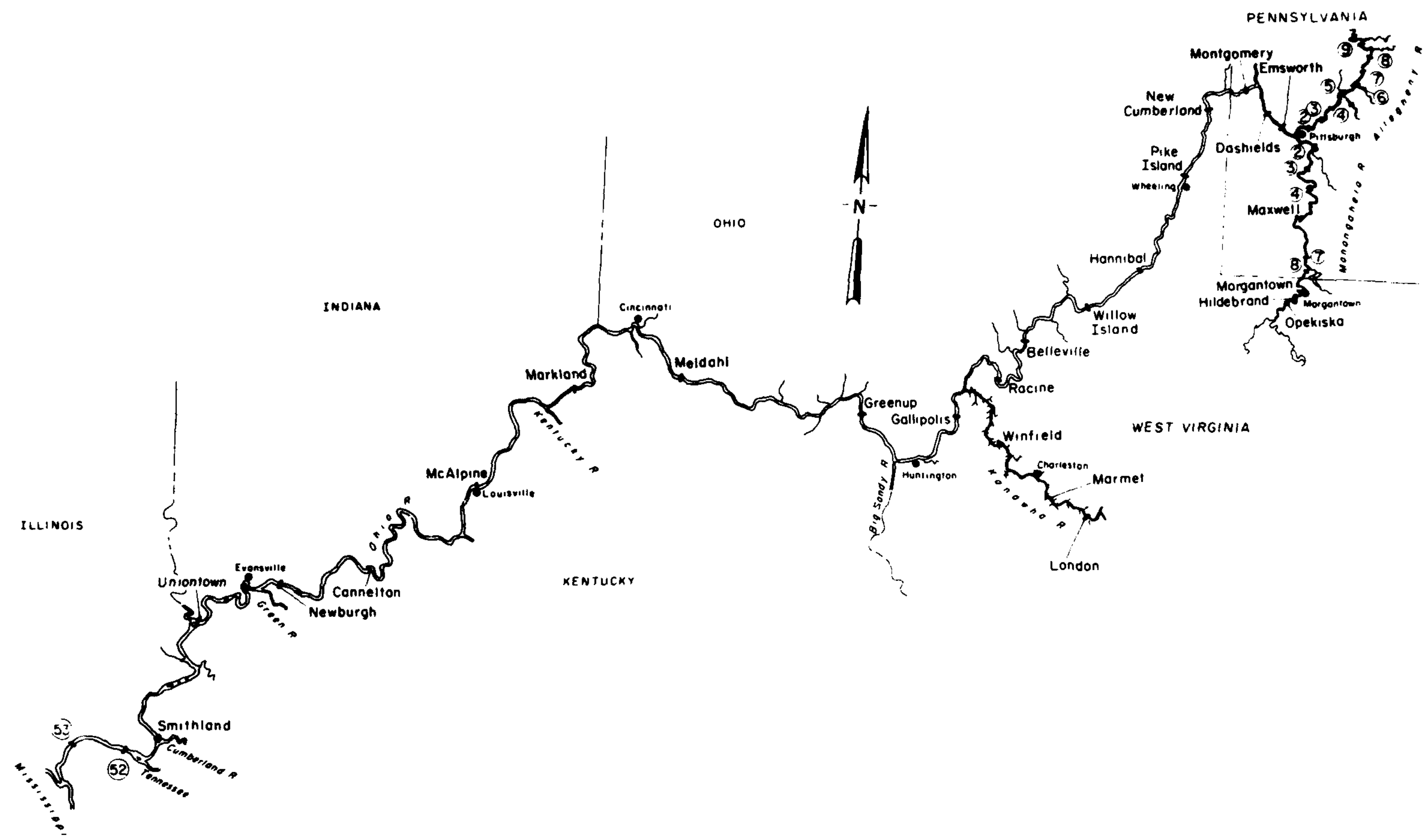

Figure 1a. Inland waterways: Ohio River and tributaries. Circled numbers are the dam designations.

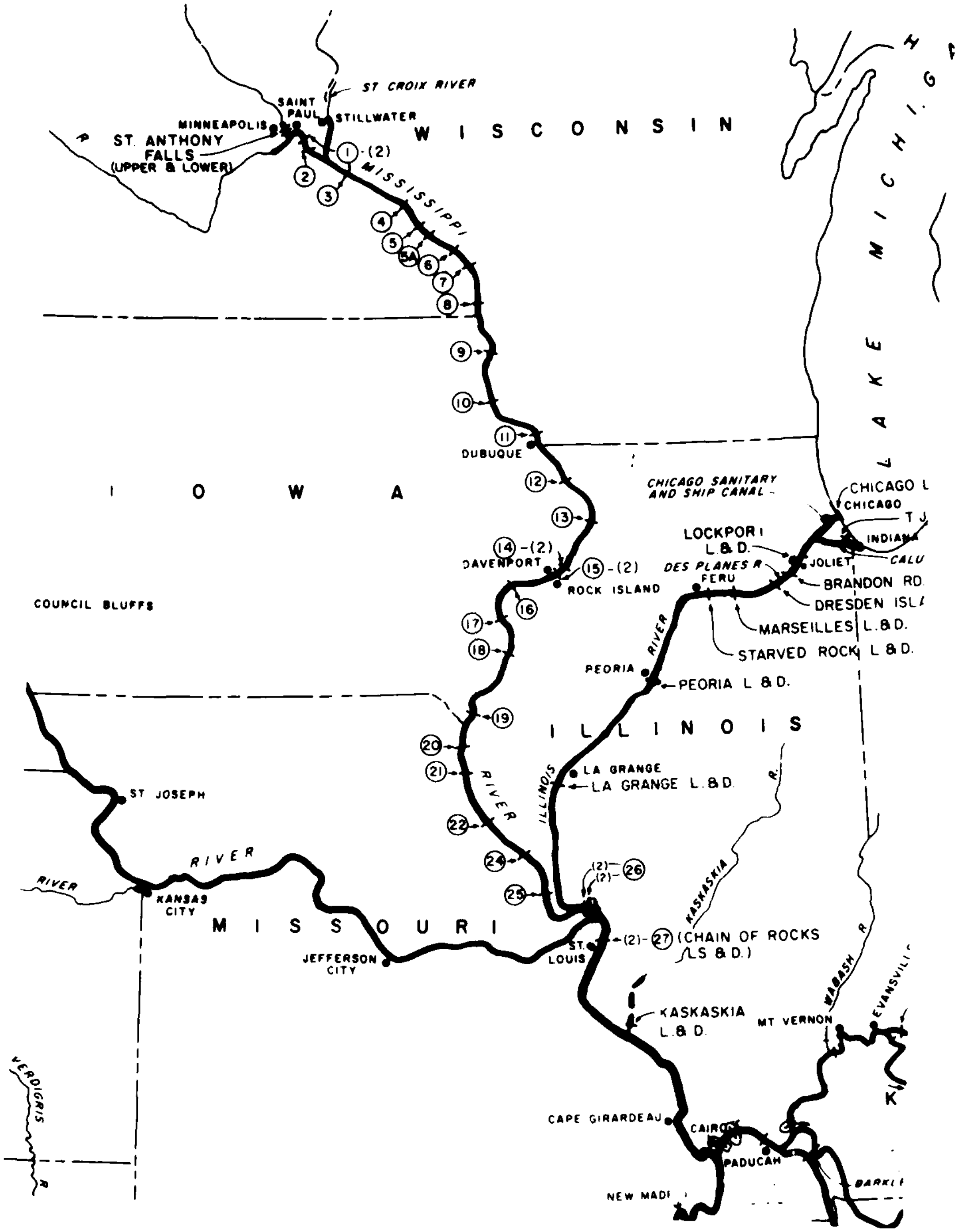

Figure 1b. Inland Waterways, Upper Mississippi River and Illinois Waterway. Circled numbers identify locks and dams on the Mississippi.

Table 1. Ohio River Locks and Dams, Ref (5)

Lock and Dam	Miles Below Pitts-burgh	Miles from Nearest Town	Type of Dam	Lock Dimensions		
				Width of Cham-ber (feet)	Greatest Length Available for Full Width (feet)	Lift (feet)
Emsworth	6.2	Emsworth, PA	M	110	600	18.0
				56	360	
Dashields	13.3	1.6 below	F	110	600	
		Sewickley, PA		56	360	10.0
Montgomery	31.7	1.4 above	M	110	600	
		Industry, PA		56	360	20.5
New Cumberland	54.4	Stratton, OH	M	110	1,200	
				110	600	20.5
Pike Island	84.3	2 above	M	110	1,200	
		Warwood, WV		110	600	21.0
Hannibal	126.4	1.6 above New	M	110	1,200	
		Martinsville, WV		110	600	21.0
Willow Island	161.7	2.7 above	M	110	1,200	
		Waverly, WV		110	600	20.0
Belleville	203.9	0.3 below Reeds-	M	110	1,200	
		ville, OH		110	600	22.0
Racine	237.5	1.5 below	M	110	1,200	
		Letart Falls, OH		110	600	22.0
Gallipolis	279.2	0.7 below	M	110	600	
		Hogsett, WV		110	360	23.0
Greenup	341.0	4.9 below	M	110	1,200	
		Greenup, KY		110	600	30.0
Captain Anthony Meldahl	436.2	2.2 above	M	110	1,200	
		Foster, KY		110	600	30.0
Markland	531.5	1 above Mark-	M	110	1,200	
		land, IN		110	600	35.0

Table 1. (Continued)

Lock and Dam	Miles Below Pitts-burgh	Miles from Nearest Town	Type of Dam	Lock Dimensions: Width of Cham-ber (feet)	Lock Dimensions: Greatest Length Available for Full Width (feet)	Lock Dimensions: Lift (feet)
McAlpine	604.0	(Reconstruction of locks and dam 41)	M	110 110 56	1,200 600 360	37.0
Cannelton	720.7	3 miles above Cannelton, IN	M	110 110	1,200 600	25.0
Newburgh	776.1	16 miles above Evan-ville, IN	M	110 110	1,200 600	16.0
Uniontown	846.0	3.5 miles below Uniontown, KY	M	110 110	1,200 600	22.0
Smithland	918.5	2 miles above Smith-land, KY	M	110 110	1,200 1,200	22.0
52	938.9	1.4 below Brookport, IL	B	110 110	600 1,200	12.0
53	962.6	10.8 above Mound City, IL	B	110 110	600 1,200	13.4

Type of Dam
F - fixed
M - movable
W - wicket (movable)
B - beartrap (movable)

Table 2. Monongahela River (PA and WV) Locks and Dams, Ref (5)

Lock and Dam	Miles Above Pitts-burgh	Miles from Nearest Town	Type of Dam	Lock Dimensions: Width of Cham-ber (feet)	Lock Dimensions: Greatest Length Available for Full Width (feet)	Lock Dimensions: Lift (feet)
2	11.2	Braddock, PA	F	56 110	360 720	8.7
3	23.8	Elizabeth, PA	F	56 56	360 720	8.2
4	41.5	Monessen, PA	M	56 56	360 720	16.6
Maxwell	61.2	Maxwell, PA	M	84 84	720 720	19.5
7	85.0	Greensboro, PA	F	56	360	15.0
8	90.8	Point Marion, PA	M	56	360	19.0
Morgantown	102.0	Morgantown, WV	M	84	600	17.0
Hildebrand	108.0	6 above Morgan-town, WV	M	84	600	21.0
Opekiska	115.4	13.4 above Morgantown, WV	M	84	600	22.0

Table 3. Upper Mississippi River Locks and Dams, Ref (5)

Lock and Dam	Miles Above Ohio River	Miles from Nearest Town	Lock Dimensions: Width of Chamber (feet)	Lock Dimensions: Greatest Length Available for Full Width (feet)	Lock Dimensions: Lift (feet)
St. Anthony Falls, upper lock	851.7	In city of Minneapolis, MN	56	400	49.2
St. Anthony Falls, lower lock and dam	851.4	In city of Minneapolis, MN	56	400	24.9
Lock and dam 1	847.6	Minneapolis-St. Paul	56 56	400 400	37.9 37.9
Lock and dam 2	815.2	1.3 above Hastings, MN	110 110	500 600	12.2 12.2
Lock and dam 3	796.9	6.1 above Red Wing, MN	110	600	8.0
Lock and dam 4	752.8	Alma, WI	110	600	7.0
Lock and dam 5	738.1	Minneiska, MN	110	600	9.0
Lock and dam 5A	728.5	3 above Winona, MN	110	600	5.5
Lock and dam 6	714.3	Trempealeau, WI	110	600	6.5
Lock and dam 7	702.5	Dresbach, MN	110	600	8.0
Lock and dam 8	679.2	Genoa, WI	110	600	11.0
Lock and dam 9	647.9	3.3 below Lynxville, WI	110	600	9.0
Lock and dam 10	615.1	Guttenberg, IA	110	600	8.0
Lock and dam 11	583.0	3.7 above Dubuque, IA	110	600	11.0
Lock and dam 12	556.7	Bellevue, IA	110	600	9.0

Table 3. (Continued)

Lock and Dam	Miles Above Ohio River	Miles from Nearest Town	Lock Dimensions		
			Width of Chamber (feet)	Greatest Length Available for Full Width (feet)	Lift (feet)
Lock and dam 13	522.5	4.3 above Clinton, IA	110	600	11.0
Lock and dam 14	493.3	3.7 below Le Claire, IA	110	600	11.0
Le Claire lock (Canal)	493.1	3.9 below Le Claire, IA	80	320	11.0
Lock and dam 15	482.9	Foot of Arsenal Island, Rock Island, IL	110 110	600 300	16.0 16.0
Lock and dam 16	457.2	1.8 above Muscatine, IA	110	600	9.0
Lock and dam 17	437.1	4.2 above New Boston, IL	110	600	8.0
Lock and dam 18	410.5	6.5 above Burlington, IA	110	600	9.8
Lock and dam 19	364.2	Keokuk, IA	110	600	38.0
Lock and dam 20	343.2	0.9 above Canton, MO	110	600	10.0
Lock and dam 21	324.9	2.1 below Quincy, IL	110	600	10.5
Lock and dam 22	301.2	1.5 below Saverton, MO	110	600	10.2
Lock and dam 24	273.4	Clarksville, MO	110	600	15.0
Lock and dam 25	241.4	Cap Au Gris, MO	110	600	15.0
Lock and dam 26 (Henry T. Rainey Dam)	202.9	Alton, IL	110 110	600 360	23.0 23.0

Table 3. (Continued)

Lock and Dam	Miles Above Ohio River	Miles from Nearest Town	Lock Dimensions: Width of Chamber (feet)	Lock Dimensions: Greatest Length Available for Full Width (feet)	Lift (feet)
New Lock and dam 26 (under construction)	200.8	Alton, IL	110	1,200	24.0
Lock 27	185.0	Granite City, IL	110 110	1,200 600	12.0
Dam 27	190.3	St. Louis, MO			

Table 4. Illinois Waterway Locks and Dams, Ref (5)

Lock	Miles Above Mouth	Miles to Nearest Town	Type of Dam	Lock Dimensions: Width of Chamber (feet)	Lock Dimensions: Greatest Length Available for Full Width (feet)	Lift (feet)
LaGrange	80.2	7.8 below Beardstown, IL	W	110	600	10.0
Peoria	157.7	4.1 below Peoria, IL	W	110	600	11.0
Starved Rock	231.0	Utica, IL	M	110	600	18.7
Marseilles	244.6	Marseilles, IL	M	110	600	24.25
Dresden Island	271.5	8 above Morris, IL	M	110	600	21.75
Brandon Road	286.0	Joliet, IL	M	110	600	34.0
Lockport	291.1	Lockport, IL	B	110	600	30.5-42.0
T.J. O'Brien	326.5	Chicago, IL	F	110	1,000	0-2

Table 5. Kanawha River (WV) Locks and Dams, Ref (5)

Lock and Dam	Miles Above Ohio River	Miles from Nearest Town	Type of Dam	Lock Dimensions: Width of Chamber (feet)	Lock Dimensions: Greatest Length Available for Full Width (feet)	Lock Dimensions: Lift (feet)
Winfield	31.1	Winfield 1 mi NE	M	54 54	360 360	28
Marmet	67.7	Belle 2 mi SE	M	54 54	360 360	24
London	82.8	London 0.5 mi NW	M	54	360	24

Table 6. Allegheny River (PA) Locks and Dams, Ref (5)

Lock and Dam	Miles Above Pittsburgh	Nearest Town	Type of Dam	Lock Dimensions: Width of Chamber (feet)	Lock Dimensions: Greatest Length Available for Full Width (feet)	Lock Dimensions: Lift (feet)
2	6.7	Aspinwall, PA	F	56	360	11.0
3	14.5	Cheswick, PA	F	56	360	13.5
4	24.2	Natrona, PA	F	56	360	10.5
5	30.4	Freeport, PA	F	56	360	11.8
6	36.3	Clinton, PA	F	56	360	12.2
7	45.7	Kittanning, PA	F	56	360	13.1
8	52.6	Templeton, PA	F	56	360	17.9
9	62.2	Rimer, PA	F	56	360	22.0

Mississippi River. The river rises in Lake Itaska, Minnesota and flows about 2,360 miles south to the Gulf of Mexico. The middle Mississippi comprises the 195-mile section from the Ohio River (mile 974 from the Gulf of Mexico) and the Missouri River (mile 1169). The upper Mississippi extends about 663 miles from the mouth of the Missouri River to Minneapolis. There are 28 locks and dams on the upper Mississippi and one lock and dam (no. 27) on the middle Mississippi.

Illinois Waterway, Illinois. The Illinois River is formed by the confluence of the Kankakee and Des Plaines Rivers in northern Illinois and flows southwest to enter the Mississippi at Grafton, IL, about 38 miles above St. Louis, a distance of 273 miles. The Illinois Waterway includes the Illinois River and also the Des Plaines River (18.1 miles), the Chicago Sanitary and Ship Canal and the south branch of the Chicago River (34.5 miles) to Chicago. There are eight locks and dams.

Kanawha River, West Virginia. The river is formed by the junction of the New and Gauley Rivers a short distance above Kanawha Falls, WV and flows a distance of 97 miles generally northwesterly to the confluence with the Ohio River at Point Pleasant, WV. There are three locks and dams.

Allegheny River, Pennsylvania. The river rises in northern Pennsylvania, flows generally northwest into New York, then generally southwest to Pittsburgh, PA where it joins with the Monongahela to form the Ohio. It is 325 miles long, but navigation is limited to the reach from Pittsburgh to above East Brady, PA, a distance of 72 miles. There are eight locks and dams.

Kaskaskia River, Illinois. The river flows from a point about 5 miles northwest of Urbana for 325 miles to the Mississippi River about 8 miles above Chester, IL. A navigable channel has been provided from the mouth to Fayetteville, IL, a distance of 36 miles. A single lock 84 ft wide and 600 ft long is located at mile 0.8 (from the Mississippi).

ICE AND THE INLAND WATERWAYS

The formation and buildup of ice depends upon meteorological conditions and the thermal and hydraulic conditions of the water system. Between the extreme of a completely open, ice-free river, and a completely unbroken, ice-covered surface, lie a number of ice conditions. Ice conditions encountered on the inland waterway have been described by Ashton et al. (6), as follows:

Open water. This condition is defined as water with no floating ice for at least the width of the normal navigation channel (defined physically by buoys).

Loose floes. This is similar to that of open water except that occasional floes and ice fragments, generally not in contact with each other, are seen floating downstream, Fig. 2.

Packed floes. This phenomenon is best described as an ice cover consisting of large floes in contact with each other but not in a jammed state, Fig. 3.

Loose brash cover. This condition is a cover consisting of many small fragments of ice, generally not of greater diameter than 6 to 8 ft and more commonly smaller, usually one layer thick, and covering the water surface entirely, Fig. 4

Heavy brash cover. This is defined as a cover of brash ice more than one layer thick over substantial portions of the surface area, Fig. 5.

Rafted ice. Ice, in this state, consists of two or more layers formed by slabs riding up onto other pieces of ice, Fig. 5. Although a stream current may cause rafting, a common cause of rafting is the passage of a tow through brash ice or an unbroken ice cover.

Refrozen brash cover. This is defined as a brash cover which has refrozen into an intact ice cover, Fig. 6. The refreezing process has progressed to the point that when the cover fractures, the original brash fragments do not separate from each other although the new fracture boundaries or cracks may follow the boundaries of the larger fragments. A more rapid stream flow may inhibit the formation of refrozen brash but it also increases the occurrence of rafting and the volume of ice collecting at locks and dams.

Unbroken cover. This is an ice cover which has not experienced passage of a tow since the closing of the previous navigation season. Essentially this is a "natural" ice cover. In some cases this term is used to refer to the ice cover through which the tow passes even though a recent track has been broken some distance away from the present track.

Jammed ice. This condition refers to an ice cover of large and small floes jammed together to the point that uninterrupted passage of the tow barges is impeded; backing and ramming are required to effect a passage through the jammed cover.

A differentiation is often made between an ice jam and an ice gorge. The Corps of Engineers (7) have, at times, chosen to make a specific and clear distinction between the terms "jam" and "gorge." The term "jam" was used to denote that situation where ice is stopped in current, bridged all the way across the river on the surface, but not obstructing streamflow in such a manner as to cause a damming effect. The term "gorge" was used to denote that situation where ice is stopped in current, bridged all the way across the river, and is obstructing streamflow in a damming effect causing

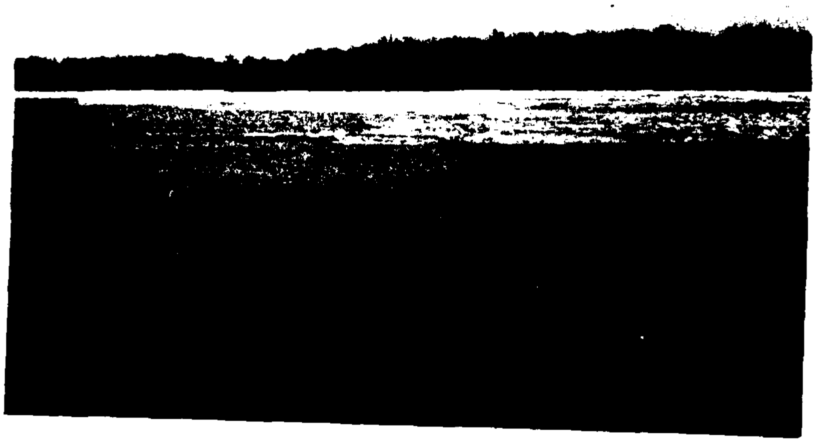

Figure 2. Loose floe ice, Mississippi River.

Figure 3. Packed floes, Mississippi River.

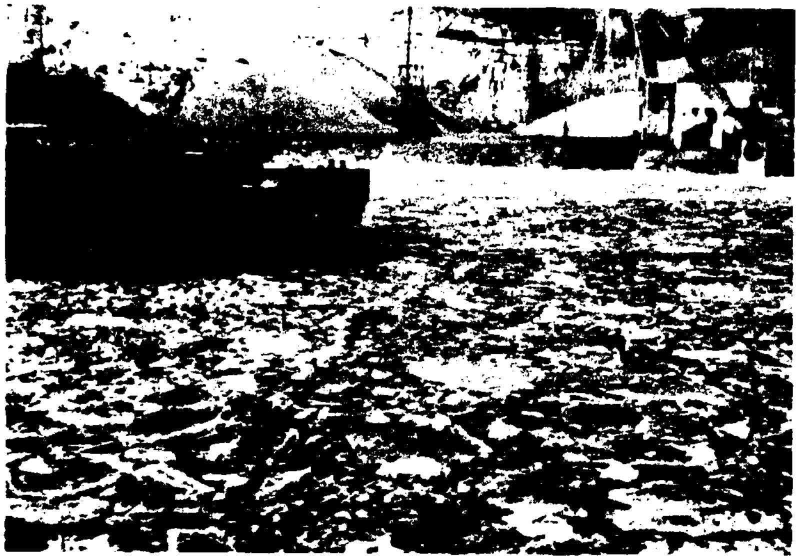

Figure 4. Loose brash ice, Mississippi River.

Figure 5. Heavy brash ice with rafted ice, Mississippi River.

Figure 6. Refrozen brash ice, Mississippi River.

head differential. However, at other times the Corps has used the terms jam and gorge interchangeably (8). A preferable definition of ice jam is an accumulation of ice at a given location which, in a river, restricts the flow of water causing an abnormal head differential (14). An ice gorge is an accumulation of broken ice which stops navigation.

Perhaps the most important single parameter needed to complete a description of a particular ice condition is its thickness. The thickness corresponds to the estimated or calculated average thickness of the ice fragments, floes or sheets. The deeper and larger pools created by navigation dams retard somewhat the formation of ice on a river. Tributary storage reservoirs, especially the deeper ones, represent a reservoir of warmer water. With freeze-over at the top, a large mass of water is insulated from further loss of heat. Release of even minimum flow from the impoundment thus represents a downstream flow which is warmer than it would have been without the impoundment. This effect dissipates with distance but data are not available to indicate the specific magnitude. An estimate can be made using a computer program (9). It is unlikely that the ice suppression will be significant.

It is known that impurities in water retard freezing. Although not constructed for that purpose, tributary storage reservoirs very effectively trap many impurities. Removal of such impurities, either by reservoir sedimentation or pollution abatement, would thus suggest a trend toward more freezing in the tributary reaches near a dam. Most waters in the eastern United States have a specific conductance less than 1000 micromhos which is nearly equivalent to a 600 ppm NaCl solution. The freezing point depression of sea water (34,000 ppm NaCl equivalent) is about -1.8°C. Thus the effect of dissolved solids may be on the order of 600/34,000 (1.8) = .03°C. During February 1967 specific conductances of the Ohio River near Markland Dam were 300-400 micromnos so the freezing point depression is likely to be on the order of .01°C. A freezing point depression of this magnitude is inconsequential for ice production calculations.

The most reliable prediction of ice thickness can be made for the condition of unbroken cover or a single layer of undisturbed ice. This type of ice will not occur if navigation traffic is frequent or if river flows and levels are modified, but it does relate the effect of weather conditions upon ice thickness and navigation.

The growth of sheet ice is given by the Stefan equation

$$X = \alpha\sqrt{I_f} \tag{1}$$

where

- X - thickness of ice, inches
- α - empirical constant related to kind of water body
- I_f - freezing index at a given location, °F-days.

The freezing index, for one day, is the difference between the freezing temperature (32°F) and the mean daily temperature. For a moderately slow moving river the coefficient α varies from 0.58 - 0.65 (10). Ice thicknesses were calculated using the equation

$$X = .62\sqrt{I_f} \quad (2)$$

The freezing indexes were calculated using the local climatological data for each city with a first order weather station (National Weather Service). These indexes have also been plotted for the continental United States by the U.S. Army (11). The freezing indexes and ice thicknesses have been plotted in Figs 7 and 8 for the area encompassing a part of the inland waterways system. An analysis of the ice problem reports for the Mississippi and Ohio Rivers allows the value of the freezing index to be correlated to the difficulty of navigation. Table 7 notes this relation but it is only a crude, first approximation and effects such as ice layering, damming, and buildup (12), and tow boat power will have a considerable effect.

Table 7. Correlation of Freezing Index and Navigation on Inland Waterways.

Freezing Index °F-days	Sheet Ice Thickness (in.)	Effect on Navigation
100	6	Little problem except for low powered tows which may require assistance.
300	12	Limit of normal navigation on upper Mississippi river with present equipment. Heavy brash ice and jamming possible. Navigation slowed. Curves in channel require backing and ramming. Possible ice damage to equipment.
600	16	Tow can break channel but high probability of damage to tow or barges. Good chance of navigation stoppage.
800-1000	20	Tow breaks channel with extreme difficulty. If layering or damming occur, navigation will cease.

Using the correlation of Table 7 and Fig. 7 it can be seen that, for average year ice conditions, only the Upper Mississippi River, Illinois Waterway and the Upper Ohio River (Allegheny, Monongahela) are likely to experience ice problems. The Mississippi River below St. Louis, and the entire Ohio River system and tributaries below Steubenville, OH should not experience significant ice problems in normal ice years. However, Fig. 8 shows the freezing index for the coldest year in 30 years. Comparable conditions can be expected for about one year in 10 which can be considered the design values. It can now be seen that significant ice problems, with

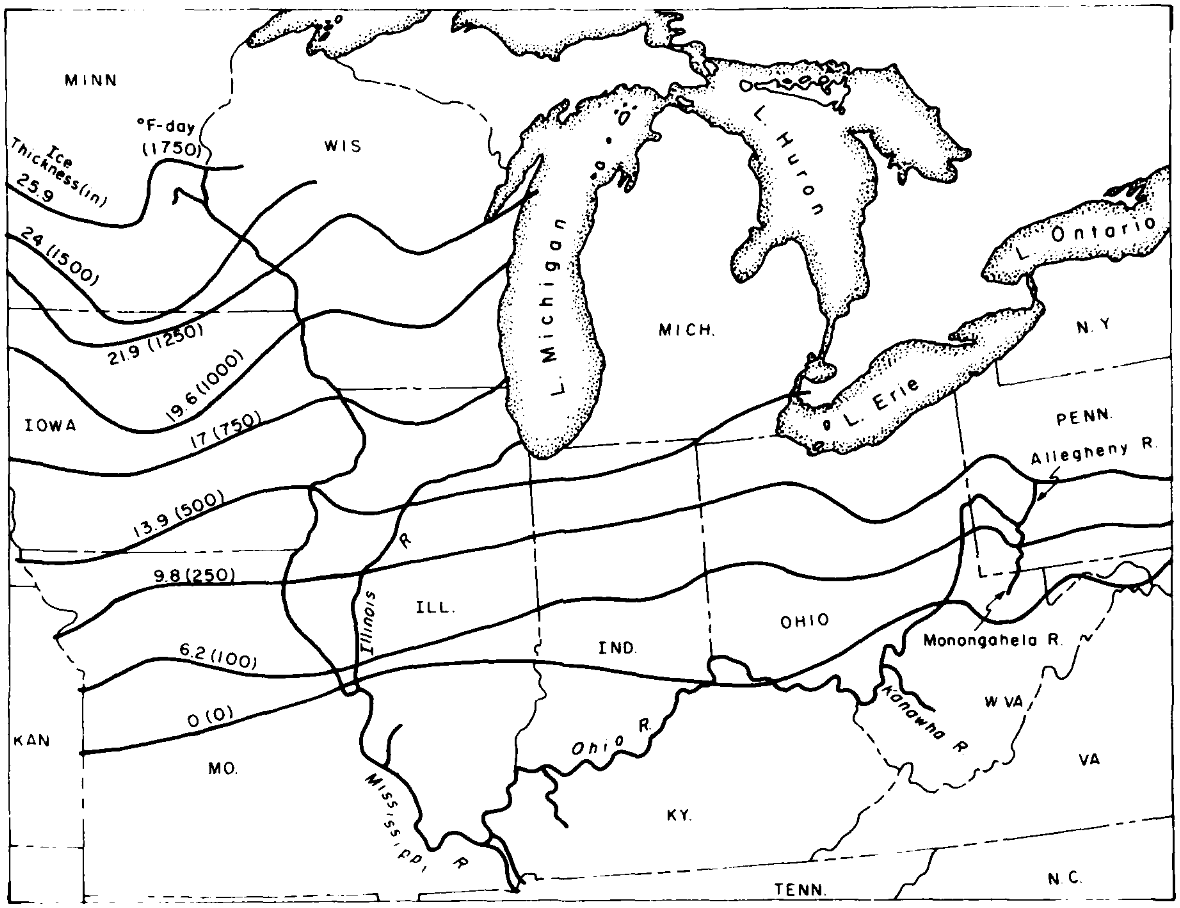

Figure 7. Mean Seasonal Freezing Index and Ice Thickness for the Inland Waterways.

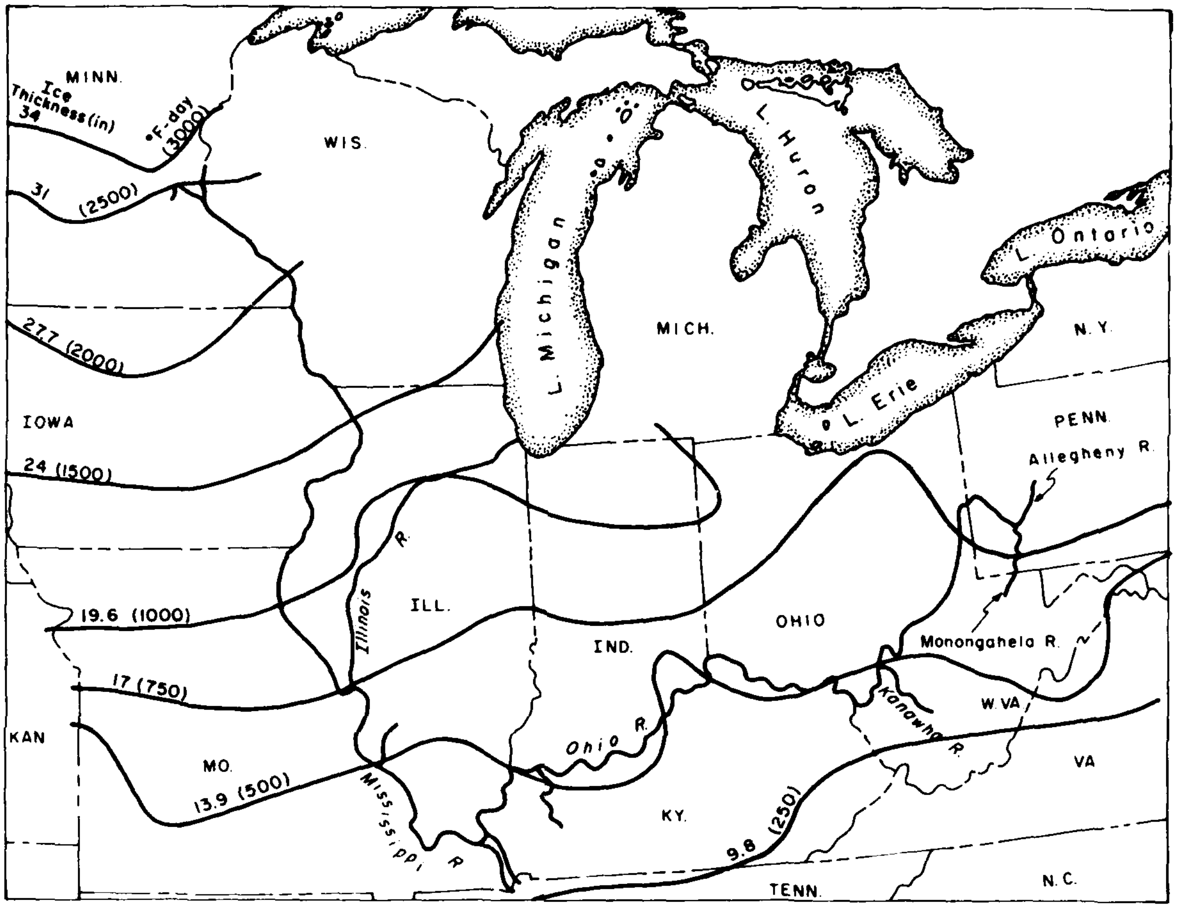

Figure 8. Distribution of seasonal freezing index and ice thickness for coldest year in thirty years, Inland Waterways.

hindrance to navigation, can be expected for the entire Mississippi River and the Ohio River system north of the Tennessee border. This would correspond to a freezing index of about 300°F-days. Less severe but still significant ice may occur about one year in three along most of the Ohio River. Thus, despite relatively long intervals without ice problems the coal handling ports along the inland waterways system must expect ice problems with some regularity.

Mississippi River Navigation and Ice

Normally the Mississippi River is navigable year round up to the Illinois River and up the Illinois River to Lake Michigan. Tow boats have navigated to Burlington, IA (past Lock 19) during a normal winter (I_f = 300°F-days). Upstream of this the season closes 15 December - 15 March (13). Thus, in an average year a freezing index of 300°F-days will be the normal limit of winter navigation on the Upper Mississippi River. However, tows have gone as far as Clinton, IA (Lock 13), where the mean freezing index is 600°F-days. In most cases either the towboats or barges sustained some ice damage. It has always been possible to lock a tow through if it reaches Lock 13, but preparation for the tow and lockage time may exceed 12 hours during very cold weather. It appears that a freezing index in excess of 400°F-days will portend ice damage to tows with a value of 600°F-days indicating a high probability of ice damage (6). Normally ice appears in December and reaches a maximum in February. There will be a lack of ice cover for a short distance downstream of a lock, except during extremely cold weather, due to agitation of the water. Without ice, tows are often 105 ft wide and up to 1200 ft long but with ice the tows can be reduced to single lines and mule training (described later) is often used, especially for bends.

Ice from the general winter freeze-up in the watershed usually converges on the Middle Mississippi River upstream of Cairo, IL, during the period 1 January - 1 March. During this time, heavy floating ice on the Missouri River, the Upper Mississippi River, and the Illinois River is usually experienced. It is generally accompanied by freeze-up of most tributaries, snow cover, and temperatures low enough to support a range of 60 to 95 percent floating ice in the Middle Mississippi River. Upstream of Alton, IL, ice forms a solid cover over the slackwater pools. Except for a traffic lane opened by towboats using the Mississippi-Illinois Waterway, the ice cover is left undisturbed in order to prevent build-up and formation of gorges and to permit passage of water flow under the ice cover. Occasionally, failure of towboats to remain in the open lane causes a breakup of the stationary ice cover which then floats downstream to mass at or above the navigation locks and dams. Retention of ice in the navigation pools on the Upper Mississippi and Illinois Rivers permits the heavy floating ice pans from the Missouri River to pass readily into the Middle Mississippi River. The presence of ice in the Middle Mississippi River downstream of St. Louis is not unusual, but severe ice massing such as that which frequently occurs on the Missouri, Upper Mississippi, and Illinois Rivers is not the norm. A severe ice problem in the Middle Mississippi River is usually the result of some combination of unusually severe weather, low flow, and/or high backwater conditions (8).

Ice problems are traditional at Mile 8 on the Missouri River near Lewis Bridge, Mile 31.5 on the Illinois River at Kampsville, and Miles 4-27 upstream of Cairo, IL. Each is upstream of the confluence with and within the backwater limits of another major river.

U.S. Army Corps of Engineers reports (15, 16) for 1968-1970 for the stretch of river from Cairo, IL to Alton, IL indicate similar but less severe ice problems compared to the reach above Lock and Dam 26. For pool 26 with a freezing index of 100°F-days, low-powered boats had trouble but the channel stayed open due to traffic. When I_f reached 350°F-days, heavy ice held traffic to one barge at a time with loose barges trapped in heavy ice flows. Heavy broken ice caused a build-up beneath barges which caused them to ground in locks causing delays and damage. Ice was passed through the lock and dam.

During 1969-70, with I_f = 118°F-days and 6 in. of ice present, traffic moved with delays of 1-5 hours. At I_f = 555°F-days and 10-12 in. of ice, tows moved very slowly. When I_f exceeded 650°F-days and the ice was 16 in. thick, there was no traffic and thus it is not possible to correlate the freezing index to the traffic. The ice jam above Cairo, IL was the main obstacle to traffic and this was due to the release of tributary ice into the main channel of the Mississippi River. The sheet ice was only 12 in. but this stacked to 5-6 ft and an ice gorge formed. Channel buoys were torn out by ice.

The winter of 1975-76 was routine with I_f = 260°F-days and ice 10 in. thick at Lock 26 (17). No navigation problems were experienced since the ice did not jam or pile up. Ice build-up on the bottom of barges estimated at 5-14 ft caused short but consistent delays. On one occasion three towboats with a combined horsepower of 2050 failed to free the barges and it required the full power of a 5000 hp towboat to pull them out of the lock (18).

Low flows and low temperatures during 1976-77 caused the worst ice conditions in the memories of veteran rivermen (8). The freezing index at Cape Girardeau, 53 miles above Cairo, IL, was about 500°F-days. This is at least twice the mean value. Beginning January 19, 1977 the river was closed between Cairo, IL and mile 160 for 27 days. At one time 500 barges were trapped in the ice (19). The normal 10-hr trip on the Illinois River from LaGrange, IL to Lock 26 took 3 days. The northern half of the Illinois River froze such that towboats could not get through on their own. Multiple towboats were used to move one or two barges. Six to eight towboats were used in coordination, to open a channel. The ice prevented dredging operations and swept away most buoy markers, further complicating navigation.

During 1977-78 Locks 24-26 experienced heavy ice and very difficult navigation with slowdowns but no major stoppage. Downbound tows at Lock 26 had to be restricted to 80 ft width, 8 barge maximum. Tows had difficulty with ice build-up on the bottom and the locks had ice problems with the miter gates.

During 1978-79 the lower 80 miles of the Illinois River had a 105 ft width restriction on tows at LaGrange Lock and Dam. Lock 26 had a 70 ft width, 8 barge maximum restriction. Seven barges were reported sunk with many loose barges stranded in ice (20).

Ohio River Navigation and Ice

Until 1977-78 no condition other than high water was severe enough to warrant predetermined closure criteria for the Ohio River (21). However, the very severe winters of 1976-77 and 1977-78 saw widespread suspension of navigation due to ice and the formation of the Ohio River Division Ice Committee in 1978 (7). Of course, navigation has been suspended due to ice many times but this has been due to the physical impossibility of moving through the ice pack rather than an administrative decision. At Cincinnati, Ohio navigation has come to a halt about once every three years, usually for very short times. The longest continuous period of suspended navigation was 65 days during 1917-18. During 1976-77, record cold and low precipitation led to ice thicknesses of 12 in. on the upper Ohio River and 18 in. on its tributaries. At Pittsburgh, PA the freezing index was 1033°F-days which is essentially the worst-case condition for a 30-year span. This freezing index correlates well to ice thicknesses of 19 in. on the Allegheny and Monongahela Rivers. Even in this severe winter the Green, Cumberland, and Tennessee Rivers escaped complete ice coverage, which can be anticipated from Fig. 7. Navigation was hampered everywhere but some tows moved continuously on the upper river system since the ice did not jam due to the low water. On the lower river it was necessary to lower the wicket-type dam gates to avoid possible ice damage. An ice jam then formed between Locks 50 and 51 and commodity movement came to a standstill from 18-31 January, 1977.

The winter of 1977-78 was significantly different. High water predominated and the type of ice was a soft, chunky ice with snow cover, which tended to form masses and ball together due to hydraulic or vessel action. This ice was passed downstream and formed massive ice jams, particularly at Markland Dam. At Pittsburgh the freezing index was 630°F-days, well below that of 1976-77, but still above average.

On the Monongahela and Allegheny Rivers ice is an every year occurrence and the ice problems of 1977-78 were not much different than in other years. However, navigation is infrequent during the winter on portions of these rivers. During this winter the heavy accumulation of ice was not a significant problem although traffic is always slowed in these conditions. The major problem was the massive ice jams due to the passage of large amounts of ice from one navigation pool to another and from tributaries of the Ohio River. At Markland Dam navigation was halted for about 19 days starting January 25, 1978. Where navigation was not halted, locking times increased to 4-5 times normal, tows were reduced and split to narrower widths.

It is impossible to decide if the ice problem is becoming more severe on the Inland Waterway but even if normal conditions prevail navigation stoppages can be expected. A systems study of ice in the system should

clarify methods to ameliorate the navigation problems.

COAL PRODUCTION AND MOVEMENT

Currently the majority of coal produced in the United States comes from the Appalachian region. In 1977 the Appalachian region accounted for 56.6% of the nation's coal production, with the midwestern states contributing 23.7%. The remaining 19.7% came from the western states. Although coal production may continue to increase in the Appalachian region, the fraction of the total from this region will continue to decrease as the western states produce more coal. The midwestern states have held a relatively constant share of the market in recent years. These trends are illustrated in Figure 9.

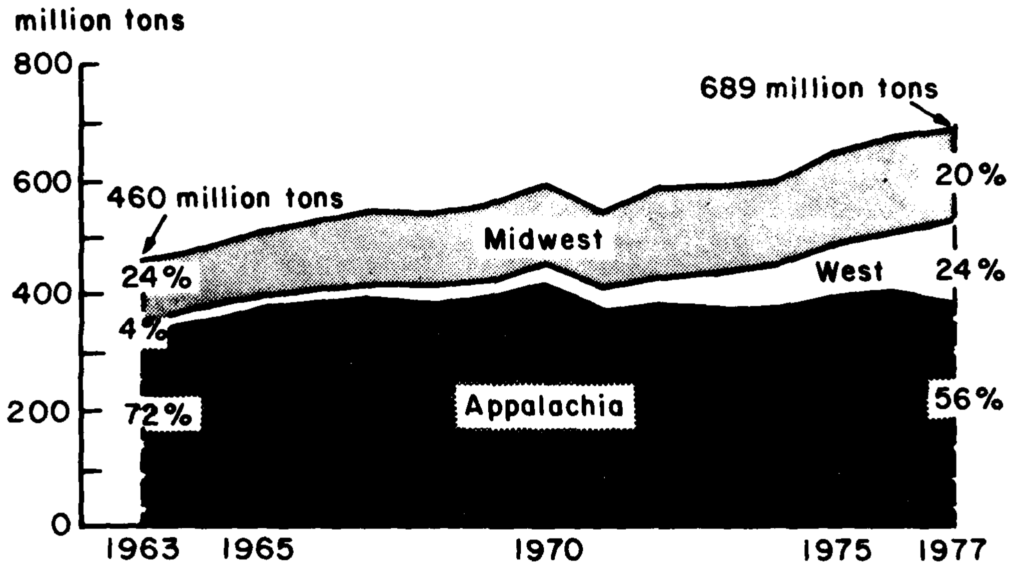

Figure 9. Trends in coal production (from ref. 23).

This report is only concerned with the effects of ice on the movement of coal on the Inland Waterways. Thus, coal production in areas which are adjacent to the rivers affected is of greatest concern. Coal from other regions may also move on these rivers, but to a lesser extent. This will tend to change as more western coal moves by water in 1990.

Many of the major coal producing states in the Appalachian region and the Midwest are located adjacent to the rivers under study. Thus, movement by the Inland Waterways has played and will continue to play an important part in coal transportation. Table 8 gives some coal production figures for the states directly adjacent to the ice prone rivers identified.

Table 8. Coal Production in States Adjacent to Ice Prone Rivers (23).

State	Coal Production (Thousands of Tons) 1963	1970	1975	1977
Kentucky	77,350	125,305	143,613	142,945
W. Virginia	132,568	144,072	109,283	95,405
Pennsylvania	71,501	80,491	84,137	83,225
Illinois	51,736	65,119	59,537	53,880
Ohio	36,790	55,351	46,770	46,205
Indiana	15,100	22,263	25.124	27,995
Missouri	3,174	4,447	5,638	6,625
Totals	388,219	497,048	474,102	456,280
U.S. Totals	458,928	602,932	648,438	688,575
Percentage of U.S. Totals	84.6	82.4	73.1	66.3

With the relative decrease of coal production in Appalachia, the percentage of the nation's total coal production which comes from these states is continually decreasing. Relative to 1970 the quantity of coal produced is decreasing but to a lesser extent than the decline of the national fraction. (Production figures for 1978, and to some extent 1977, are unusually low due to the 111 day labor strike lasting from 6 December 1977 until 26 March 1978.)

Coal moves from the mines to the areas of use by three major modes: rail, water, and highway. Railroads carry the major portion of the coal, with barges and trucks sharing the rest nearly equally. Table 9 gives the breakdown by primary transport mode for several recent years. (In instances where coal moves by more than one mode from its point of origin to point of use, the primary mode is considered to be the one moving it the greatest portion of the total trip.) These percentages have remained relatively constant over the period shown. Studies on this subject indicate that this will probably also hold true in the future (23). In 1977 total US coal production was 688.6 million tons (23). During that same year 212.0 million tons of coal were moved at some point by water (25). This includes all shipment of coal and in isolated instances the same coal may be shipped and counted more than once, and thus it is somewhat high. The numbers indicate that about 31% of the nation's coal production moves at some point by water. In 1977 coal and coke shipments accounted for 16.3% of the domestic waterborne commerce.

Ice-prone rivers carry a major fraction of the coal shipments. Tables 10 and 11 give the coal movement on the ice-prone rivers identified during 1977 and 1978. The coal movements on these rivers alone represent over 68% of the total waterborne coal shipments. Coal is a major, if not the predominant, commodity shipped on each of these rivers. Overall, coal re-

Table 9: Relative Percentages of Primary Coal Transport Modes (23)

U.S. COAL PRODUCTION AND TRANSPORTATION BY MODE*, 1968-1976
(percent of total production)

		1968	1969	1970	1971	1972	1973	1974	1975	1976
PERCENT OF TOTAL MOVED	Rail	73	71	68	69	66	67	66	65	64
	Motor Vehicle	11	12	12	11	11	10	11	12	13
	Mine-Mouth Generating Plants	(a)	(a)	6	9	11	11	12	12	12
	Barge	12	13	13	11	12	12	11	11	10
	Other**	4	4	<1	<1	<1	<1	<1	1	1
MILLION TONS	Total Production	545	560	603	552	595	592	603	648	679

(a) Included in "Other."

* Primary transport mode used to move coal from mine to final destination.

** Includes coal used at mine, taken by locomotive tenders at tipple, used at mine for power and heat; coal transported from mine to point of use by conveyor or tram; coal made into beehive coke at mine; all other uses at mine; and coal shipped by slurry pipeline. Until 1970 includes coal used at mine-mouth generating plants.

Table 10: Coal Movement on Ice Prone Rivers During 1977 (24).

River	Coal Transported (Thousands of Tons)	Total Cargo (Thousands of Tons)	Coal as % of Total Cargo	Doubled Coal Movement - Coal as % of total cargo
Ohio	81,181	151,372	53.6	69.8
Monongahela	28,411	34,420	82.5	90.4
Mississippi:				
a) Mouth of Ohio to mouth of Missouri	10,680	74,306	14.4	25.2
b) Mouth of Missouri to Minneapolis	9,056	67,021	13.5	23.8
Illinois	6,518	40,660	16.0	27.6
Kanawha	5,841	10,756	54.3	70.4
Allegheny	1,889	5,085	37.3	54.3
Kaskaskia	1,185	1,287	92.1	95.9
Totals	144,771	384,907	37.6	54.7

Table 11. Coal Traffic on Ice Prone Rivers During 1978 (26).

River	Coal (Thousands of Tons)	Total Cargo (Thousands of Tons)	Coal as % of Total Cargo
Ohio	73,934	152,589	48.5
Monongahela	24,880	31,674	78.6
Mississippi River			
a) Minneapolis to mouth of Missouri River	6,495	68,816	9.4
b) Mouth of Missouri River to mouth of Ohio River	8,603	79,161	10.9
Kanawha	5,802	10,993	52.8
Illinois	3,852	37,113	10.4
Allegheny	1,702	4,405	38.6
Kaskaskia	1,413	1,883	75.0
Totals	126,680	386,634	32.8

presents 37.6% of the total cargo shipped on these rivers. Since coal shipments represent such a large fraction of the total shipments for the Ohio, Monongahela, Kanawha, Allegheny and Kaskaskia Rivers, traffic conditions on these rivers are very much dependent on the amount of coal movement. If, for instance, the amount of coal being transported on any of these rivers were to double the total traffic on that river would significantly increase. If the river system under question is operating at or near capacity before such an increase, bottlenecks could result. Some instances where portions of particular river systems are at or over design capacity will be discussed later.

DAMS

Navigation dams are constructed across a river to control channel depths, to reduce fluctuations in current and level and to create pools stable enough to enable operation of terminal facilities. Two principal types of non-navigable dams are used on the inland river system: fixed crest and movable crest. In addition, navigable dams were used widely in the early days of the development of the river system, and a few are still in use.

a. Fixed crest dam. As the name implies, the main damming surface is fixed at some height above the stream bed and surplus water flows over the top or through openings in the fixed structure. Ice will flow over the top of a fixed crest dam and will add to ice formed in the lower pool. The greater amount of floating ice can affect terminal operations and increase the probability of ice jam formation.

b. Movable crest dam. The main damming surface can be raised out of the water or lowered towards the stream bed to permit flow of surplus water. Roller gates, tainter gates, and vertical lift gates are the commonly used types of movable crest dam. Tainter gates that are raised allow the water to pass underneath. The submergible tainter gate can be lowered to allow surplus water to flow over the top. Ice can also pass over or under the movable gates.

c. Movable dam-navigable. In this type the damming surface can be lowered to the stream bed for the passage of floods, with no in-stream obstacle to navigation. The movable gates are called wickets, and are essentially wooden or steel shutters supported in an inclined position by props or struts. Water pressure holds the wicket in place against the prop and the bottom sill. As with the fixed crest (non-navigable) dam, ice can flow over the top at high water stages but there is some risk of ice damage.

BARGES AND TOWBOATS

Towboats (which are somewhat misnamed because they push a group of barges lashed together as a unit to form a tow) range in horsepower from several hundred to 10,000. Small towboats of around 700 hp are used on the Monongahela, Allegheny, Kaskaskia, and Kanawha Rivers where lock dimensions and winding channels limit the size of a tow to four or six barges. The larger towboats are used on the Mississippi and Ohio Rivers, and sometimes on the Illinois Waterway, for propelling tows up to 15 barges, configured three abreast and five long. A tow of this size can penetrate about 5 in. of ice, but must be reduced in size if ice is thicker.

Two sizes of barges predominate for hauling coal. The jumbo is 195 ft long and 35 ft wide with a capacity of 1400-1450 tons. The standard barge is 175 ft long and 26 ft wide with a 850-950 ton capacity. A less common version is the stumbo, 195 ft long and 26 ft wide. A barge with square ends is called a box barge, and one with a sloping hull fore and aft is called a raked barge, see Fig. 4. The combination type, one end raked and the other square, is called a semi-integrated. Raked bows are usually placed at the front of a tow, a practice which is particularly desirable when the tow is being forced through an ice cover since the bow rides up onto the ice sheet and causes ice to fail in its weakest, bending, mode. There is less tendency for a raked bow to drive a brash ice prow in front of it, since the broken ice is displaced downwards.

When a tow moves through ice fields, some ice can adhere to the bottom and sides of the vessel and, of course, reduces the efficiency of the towing operation. The ice build-up on the bottom of tows is occasionally troublesome because the ice in many instances prevents the tow from crossing the miter gate sill. A number of tows get stuck at the sills and much time is lost as a result. Also, when the water level in the lock chamber is lowered, the tow may come to rest on the lock floor owing to the accumulation of ice on its bottom. This creates a strain on the ratchets and rigging which tie the tow together. This occurrence is rather infrequent and is not considered a major problem.

Empty, open barges also will build up ice on the bottom when air temperatures are below freezing. It is not unusual for a thickness of a few feet to accumulate (given a large enough freezing index) and, if augmented by the broken ice during towing, this increased draft can cause the barge to touch the channel bottom or to contact lock sills during entry. Few cases of serious damage to either barges or locks have been reported due to this; however, it was reported that a barge was broken in half when an ice accumulation in the center of the barge contacted the lock floor during the drop to lower pool level.

The increased draft of an iced barge may require reduction in load to prevent grounding in shallow channels and at lock sills, but in any case the increased hydrodynamic resistance represents a fuel penalty. No attempts are made to control ice accretion on barge bottoms. Ice that may

adhere or form on the sides of barges and prevent close coupling during fleeting is removed, however.

Barge hulls are covered with steel sheet normally 3/8 in. thick. This is sufficient to penetrate ice with no damage. However, barges that have been in use for many years may have thinner skins because of rusting and abrasion, and ice can hole them. At the time when barges cost around $30,000 and extensive rust treatment cost $10,000, there was insufficient incentive to reduce rusting. Today, barges cost around $275,000 and rust treatment still costs around $10,000 so rust treatment is more common now. Thus the incidence of holed barges will decline in the future.

WINTER PROBLEMS AND CURRENT SOLUTIONS

The effects of ice and winter weather on coal movement on the Inland Waterways can be subdivided into three areas which are interrelated. The first phase of the transport pertains to the transfer facilities from land transport to the water transport system, i.e., loading and unloading facilities. The second phase concerns the actual navigation channel. The connecting links between the channels are the locks and dams which comprise the third phase. Each of these parts of the system has characteristic problems with some ice problems common to all.

Problems at Locks and Dams

The following details describe the major ice problems experienced at locks and dams. Solutions which have been used to ameliorate these problems are taken from (21), from on-site visits, or from work done by USACRREL.

Broken Ice in Lock Chamber. A considerable amount of ice is pushed in front of downbound tows (see Fig. 10-13). In order to get the tow into the lock, the ice is pushed by the tow into the lock and the ice is locked through first. Two ice lockages are sometimes needed. There is a problem in getting all of the ice flushed out, and the locking-through of ice results in delays to shipping. Also, the process usually draws more ice into the upper lock approach, making it more difficult for the next downbound tow.

Other solutions used:

a. Downbound traffic breaks up ice and passes it over the emergency gates (for those locks so equipped).

b. Lock chambers are filled and emptied approximately every two hours to break ice around gates when traffic is light or nonexistent.

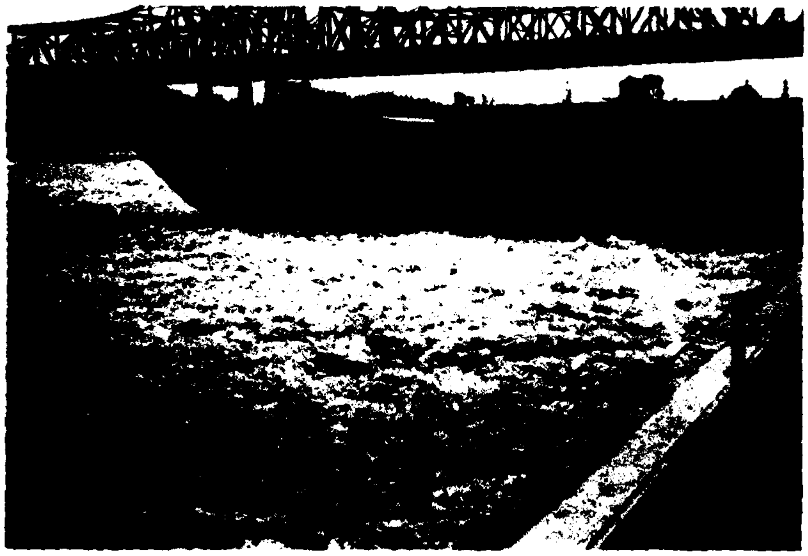

Figure 10. Ice pushed into lock, Illinois River.

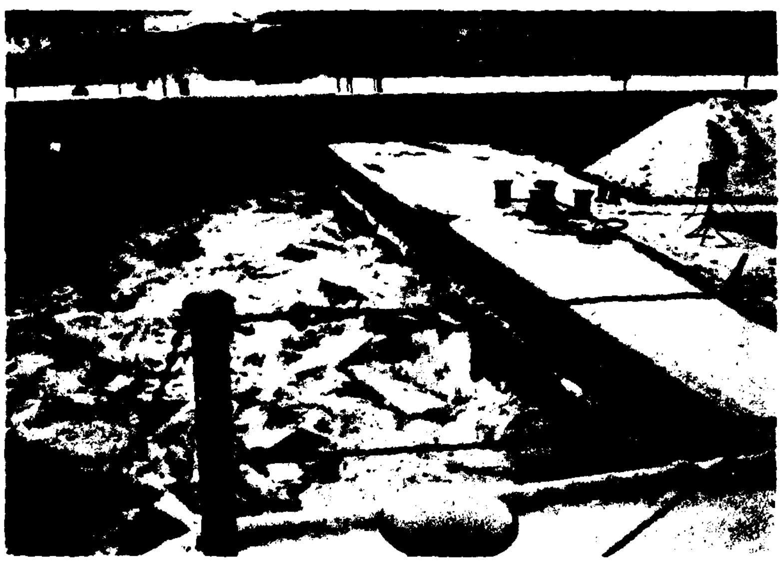

Figure 11. Ice pushed into lock chamber with tow.

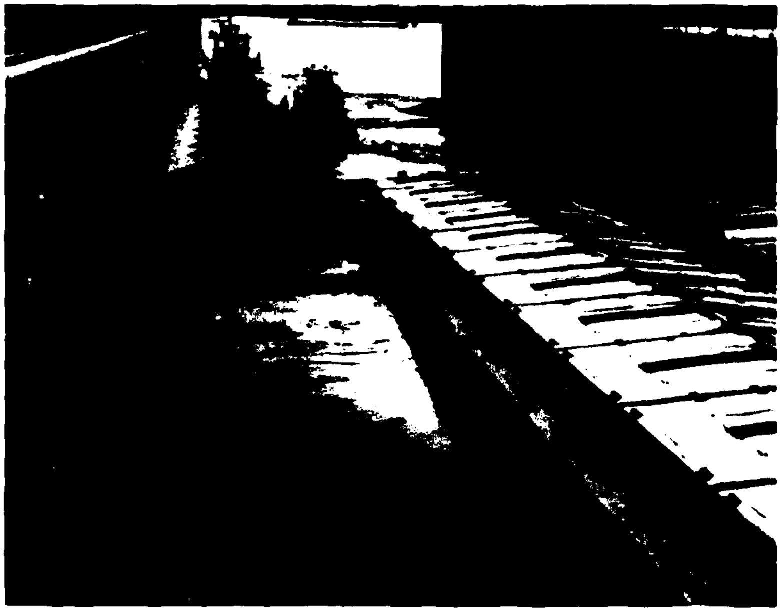

Figure 12. Ice pushed into lock by tow, Lock and Dam 26, Mississippi River.

Figure 13. Lock clearance reduced by ice, Lock and Dam 26, Mississippi River.

c. A high flow air screen has been used successfully at the Poe Lock, Sault Ste. Marie, Mich. (27). The air screen creates a high enough horizontal water velocity in the upstream direction to hold back and deflect the downbound ice being pushed ahead of traffic. In addition to deflecting the brash ice flow there was less wear and tear on the lock gate and mechanisms and a reduction in the time and effort required to remove ice buildup on the lock walls. Air screens are now being used on the Ohio River at Emsworth, Dashields, Montgomery, New Cumberland, Pike Island, Hannibal, and Markland and on the Mississippi River at Lock 21.

d. Ice can be diverted through existing auxiliary locks if a suitable ice flow diversion structure is positioned upstream of the regular lock. An air screen might be suitable as the flow diversion device.

Lock Miter Gates. One of the major problems in winter navigation is the operation of the lock miter gates. Broken ice drifts or is pushed by tows into the gate recesses (see Figs. 14 and 15). This is an especially difficult problem at the upstream gates. Also, during cold weather, ice forms on the walls of the miter gate recesses (see Figs. 16 and 17). Lock gates must be fully recessed if tows are to be provided full lock-width clearance. Less than full lock-width clearance could result in delay of traffic. When gates are not fully recessed they are in a vulnerable position and could be severely damaged by tows.

Solutions used:

a. Boat wheelwash used to flush ice from behind gates (see Fig. 18 and 19).

b. Ice chopped by hand using axes, picks, bars, pike poles, or special tools, e.g., 26 ft long ice pike pole Fig. 20).

c. Lock water level left in lowered position, with gates closed, so sun can melt ice.

d. Compressed air used to flush out ice from behind gate.

e. 10 x 12 in. oak blocks on ropes lowered between gate and wall; opening the gate cracked ice off the face of the gate and wall.

f. Air bubbler systems are operated at Locks Nos. 1, 19, 24, 26 and 27 on the Mississippi River. These systems are effective in preventing ice from forming in the gate recesses. The principle of retarding ice formation with a bubbler system relies on the upward movement of warmer sub-surface water by use of air bubbles. Compressed air is released from the bubbler in the vicinity of the warm water reservoir. Since air is lighter than water, the air will rise, carrying some of the warmer bottom water toward the surface. The warmer water and the turbulence created when the air bubbles reach the surface are often sufficient to prevent ice formation, depending on the existing atmospheric conditions, temperature structure of the water, and the quantity of water transported (28). For a

Figure 14. Ice behind miter gate.

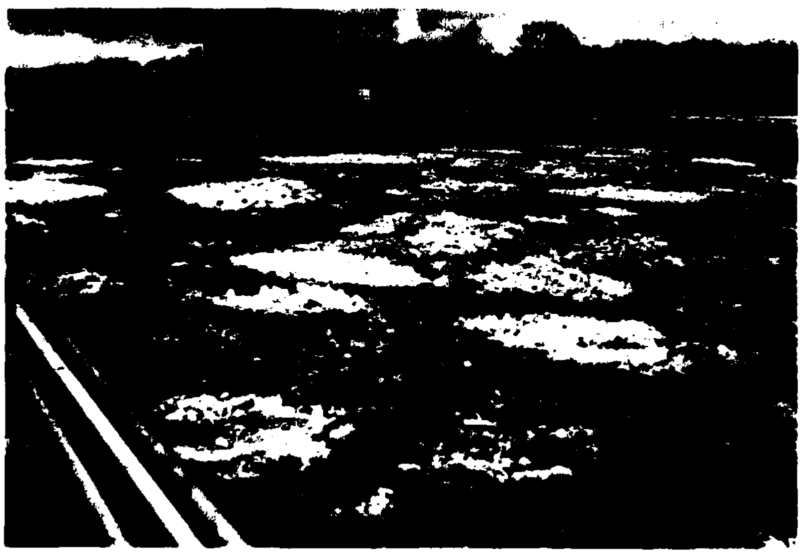

Figure 15. Brash ice collecting above miter gate, Illinois River.

Figure 16. Ice in miter gate recess, Illinois River.

Figure 17. Ice in miter gate recess, Starved Rock Lock, Illinois River.

Figure 18. Switch boat clearing ice from miter gate with wheelwash, Lock and Dam 26, Mississippi River.

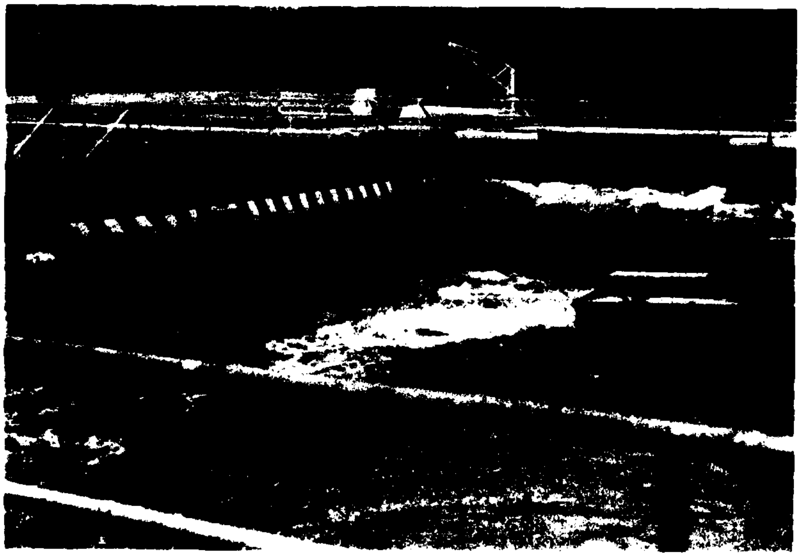

Figure 19. Wheelwash used to clear ice from miter gate, Illinois River.

Figure 20. Pike pole used for chipping and moving ice, Illinois River.

well mixed river there may be no significant layer of warm water to be entrained to the surface and thus the agitation or turbulence created in the gate recesses by a bubbler system is more important. Such turbulence is needed to flush loose ice out of the gate recesses. During 1978 bubbler systems on the Ohio River could not keep up with the ice buildup within the gate recesses. This necessitated considerable hand labor to keep the gates operational.

Suggested solutions include:

a. Sand and gravel aquifers exist adjacent to many of the Mississippi River locks and dams. Wells in these aquifers can produce more than 500 gpm, with the temperature of the water ranging from 45° to 55°F. This warm water could be used to prevent icing in the gate recesses (13).

b. Submersible pumps could be used to generate currents to move ice out of the recesses. This concept has been investigated by USACRREL with little success.

c. The use of an insulating blanket of foam may keep water from freezing in the recess.

d. Electric or steam heating systems may be feasible despite the problem of energy availability. About 500,000 to 750,000 Btu/hr per miter gate leaf may be required (7). With a 60-day season and energy at $8 per million Btu the cost would be $11,000-17,000 per mitre gate. This is probably excessive.

e. High pressure air as used on Great Lakes and St. Lawrence Seaway locks.

Ice Accumulation on Lock Walls and Gates. During very cold weather, ice accumulates on the side of a lock wall at the upper pool level each time a lockage is made. Eventually, an ice shelf is formed at the upper pool elevation (see Figs. 21-23). This shelf may be as much as four feet wide at the top, tapering to about nine inches thick at the lower pool elevation. Tows entering the locks often have ice on their sides and the ice knits to the ice on the lock walls, causing a greater accumulation (see Fig. 24). There is also a build-up of ice on the lock gates. It sometimes is necessary for the Corps to restrict the width of a tow entering a lock to two or even one barge width because of ice build-up.

Solutions available:

a. U.S. Army Cold Regions Research and Engineering Laboratory (29) has developed an ice cutting saw, mounted on a tractor-trencher, specifically for cutting ice from the sides of lock chambers. Ice collars about 6-8 ft deep can be cut at 10 ft/min leaving about 1 in. of ice on the wall.

b. A chemical coating is available which reduces the adhesive force between a coated surface and the ice that forms on it (30). While ice formation is not prevented, the ice removal is greatly facilitated. A mixture of GR 5330 (block co-polymer of polycarbonate and dimethylsiloxane), 10% silicone oil, and toluene-methylisobutylketone solvent was most effective. Three coats of 1-2 mil thickness each are recommended.

c. Embedded heating cables or steam pipes along the lock walls.

d. Melting with space heaters has been carried out but this is limited to relatively minor icings.

e. High velocity air screens will act to prevent the ice from entering a lock and thus will reduce the ice buildup on the lock walls.

Passing Ice at Navigation Dams. There are periods during the winter when large quantities of broken ice are passed at the navigation dams. The ice floes are caused by movement of the ice cover on the navigation pools and/or ice movement into the main channel from tributary streams. Normally the ice is passed by raising the tainter gates and letting the ice flow beneath. At times the navigation pool may be drawn down rapidly to put pressure on the ice jam to break it loose and start it moving.

Tows often get caught in ice gorges. With tows or barges stuck in the ice, it becomes even more difficult to pass the ice at the dams, because the trapped barges move with the ice toward the dam. Generally, in the past, towboats with sufficient horsepower have moved into the ice gorge and removed the trapped barges before they reached the dam.

A bubbler system as described earlier could possibly be used to keep the water open in the vicinity of the dam. Also, a path from the upper

Figure 21. Four feet of ice buildup on wall of Starved Rock Lock.

Figure 22. Ice buildup on wall of Starved Rock Lock.

Figure 23. Ice buildup in a miter gate recess, Illinois Waterway.

Figure 24. Brash ice wedged onto lock wall by barge.

lock gate approach to the dam might be kept open, so that ice coming down the river could be diverted to the dam.

On the Illinois Waterway, small boats are used to keep ice broken around the dams to facilitate passing the ice over the dams. These boats are normally used to adjust the wicket dams and in wheelwashing ice away from the lock gate recesses (see Fig. 19).

Snow and Ice on Lock and Dam Machinery. Provision must be made to keep ice from forming on and adjacent to lock valves. If ice were to form, a valve might wedge in the up position and later slam shut when it is freed. The sudden closing of the valve is highly undesirable. The latching devices within emergency bulkheads freeze after being submerged and raised in freezing air. Air lines often freeze up and culvert valves, levers, cables, etc. are all prone to ice loading. Culvert valves often freeze so that they cannot be opened or closed completely. Spalling of concrete has occurred due to freeze cycles and de-icers. Gate raising motors sometimes overheat when raising ice-loaded gates.

Solutions used include:

a. Anti-freeze is inserted into the air line valves every 8 hrs. Air activated devices could be changed to hydraulic to prevent freezing.

b. Propane torch and hot water has been used on frozen air lines.

c. Shovel off snow, chip ice by hand.

d. Ice chipped off culvert valve arm or melted with kerosene torch.

e. Acetylene torches used to melt ice from rods of gate valves.

f. Heaters installed on valve controls.

g. Shield mechanisms from weather.

h. Keep emergency gate in stored position when not in use.

i. In the past when winter operation was required, the miter gate machinery pits at a number of locks have been covered with a tarpaulin, plywood, or an aluminum sheet to help trap the heat. On some occasions small heaters were installed. If ice does form on the machinery, hot water or steam is sometimes employed to melt the ice.

j. Increase the size of gate motors and machinery.

Freezing of Floating Mooring Bitts. The floating mooring bits (see Fig. 25) tend to freeze in place and are no longer useful for the locking operation. This problem has not been solved satisfactorily. Some solutions attempted include:

Figure 25. Floating mooring bitt in lock chamber wall, Monongahela River.

a. Hot water poured around ice on the bitt.

b. Prevent freeze by slowly and continuously raising and lowering the lock chamber water level.

Problems In Navigation Channel

Streamflow rate has an important bearing on the presence, type, quantity, and location of ice. An open river, one on which no dams have been constructed, has no flow control, and the current will vary widely from very swift during periods of heavy rainfall and/or high runoff to very slow during the dry season. Daily level changes are not generally extreme. Flow is normally reduced during the winter because of the unavailability of water over the watershed. For example, a gage of 12-18 ft is necessary at St. Louis for good flow to move ice in the channel; a typical winter gage is 2-3 ft. Allied with the low flow is the shallower channel depth, maintained at the summer stage of 9 ft minimum by dredging. The depth can drop to 7 1/2 ft, in which case the draft of the barges must

be reduced by loading less cargo and a jumbo load will drop from a normal 1450 tons to 1200 tons. As described later, propulsion force increases as the channel depth decreases.

Dams create deep reservoirs (the upper pool) where the water is generally quiescent. The water level or stage can vary to a much greater extent below the dam (the lower pool) and the stream flow is much swifter there. This frequently reduces ice problems at docks within a few miles downstream of a dam because of the scouring action. As an example, the Bruce Mansfield generating station of Pennsylvania Power is about 1.3 miles below Montgomery Dam on the Ohio River, near Shippingport, PA. Rapid rise of water level can occur in the lower pool - 8 ft in 8 hours has been observed. This can stop coal unloading because barges are not able to fit under the continuous bucket unloader. In contrast, ice at the terminal has never prevented unloading operations, although heavy ice in other reaches of the river prevented coal from reaching the terminal.

The W.H. Sammis plant of Ohio Edison is located 1 mile upstream of New Cumberland Lock and Dam on the Ohio River. Considerable broken ice (called "sandwich ice" locally) collects along the dock and jams along the shore. This shut down unloading operations for three months in 1978, and frequently requires ice breaking with a large towboat (in the 7200 hp range) even in less severe winters.

Ice Fields. Often, tows get caught in ice fields which may extend to the bottom of the channel. When this happens, the pilot has practically no control over the tow. A tow held in an ice field may pose a threat to a navigation structure as well as to the tow. While they were not a threat to navigation structures, during 1976-77, over 500 barges were trapped in the ice above Cairo, IL (19).

Ice Gorges. It is extremely difficult, and in some instances impossible, to navigate through an ice gorge. In some cases a tow can work its way upstream through a small gorge, but with extra wear and tear on the wheels and rudders of the boat . Multiple boats have been used simply to move one or two barges. Such a task is time-consuming and requires a great deal of skill on the part of the pilots. Floating plant also suffers from the action of the ice gorges which often occur on the Upper Mississippi River. Ice may move out of one or more navigation pools and gorge in a downstream pool. Usually a cold period followed by a warming trend, accompanied by above-normal river flow, will cause the ice to move and gorge. Often weather conditions will cause ice from tributary streams to move and pile up in reaches of the main channel.

Operating procedures. Some special techniques have been developed for navigation during the winter.

a. Mule training. In this procedure the towboat pushes a single barge and tows the remainder of his string with cables. This increases

control and maneuverability in ice, and facilitates passage of the broken ice past the tow because of turbulence from the towboat's screw ("wheelwash"). This technique is of advantage for navigating river bends.

b. Double locking. A tow that is too long to fit in a lock must make passage in sections. This can happen at any time of the year; however, a tow that might fit in a lock in a single pass in the absence of ice may have to double lock when ice in the lock prevents all the barges from entering. This can sometimes be avoided by locking through the ice that collects in the upper pool before a tow arrives at the lock. If ice is pushed into the lock ahead of the tow it may be necessary to double lock. The tow enters the lock to the full extent possible, then the barges that exceed the lock capacity are backed out by the towboat, the gates are closed and the water level changed. The barges in the lock are then winched out by cable, the gates are closed and the level changes to that of the remaining tow. The procedure is then repeated as many times as necessary to pass all the barges and the towboat through the lock.

c. Double tripping. This is similar to double locking but requires the towboat to enter the lock during each locking through at those locks that have no provisions for winching.

d. Two-boat tows. In severe ice conditions a towboat oriented backwards may precede the main tow. The wheelwash of the pilot towboat serves to weaken the ice which is then displaced by its passage (Fig. 26).

Ice breaking is accomplished by industry without the use of specialized equipment. Towboats can cope with the ice that normally forms on the lower Mississippi, Ohio, Monongahela, Allegheny and Kanawha Rivers and the Illinois Waterway. Only the extreme conditions such as occurred in the winter of 1976-77 exceed the capability of towboats for effective ice breaking. The upper Mississippi, however, above Lock and Dam 19, is normally closed to shipping during the winter because of heavy ice. If a full tow (generally 15 barges) cannot penetrate an ice cover, the tow size is reduced until in extreme cases only a single barge is pushed. The turbulence created by the towboat propeller is used to advantage to break the ice around docks. A towboat alone is also used as an ice breaker when ice has jammed to such an extent that barges cannot penetrate. This is frequently the case in lock approaches, where the current has driven ice. When a gorge forms even the highest powered towboats may be unable to clear a channel. Consideration should be given to the design of efficient specialized ice breaking vessels for use in freshwater; some designs have already been built and tested in West Germany.

Tows moving through an ice cover have much more difficulty in executing river bends than when moving on a straight course. Mule training, described elsewhere, is effective for navigating river bends but reduces the size of a tow.

Figure 26. Towboat reversed to utilize wheelwash to clear ice, Mississippi River.

Ice often forms on the sides of barges prior to fleeting and unless dislodged prevents the necessary close contact when a tow is made up. Brute force methods are used to break off this ice, such as by pike poles or axes.

Many suggestions have been made concerning actions to prevent the formation of ice and its problems in the navigation channels. Among these are:

a. Constant traffic. Maintain constant traffic in the channel to inhibit fusing of ice floes. The repeated breaking and re-breaking of a channel will produce more ice if the ice can raft or move out of the immediate channel.

b. Fluctuation of flows. Using the flow control capabilities (dams and other control structures) of the Inland Waterways to fluctuate the water levels in a manner such that ice plate fusing is inhibited.

c. The use of heated condenser water from power plants has been proposed as a method of keeping a river channel open during the winter. However the channel kept open by cooling water is very narrow and the benefit would be felt only in the immediate vicinity of the plant (9). Furthermore new power plants do not use the once-through method due to regulations on the maximum allowed summer temperatures of the river.

Some of the following breakup actions could also be used as preventive actions:

a. Melting. Alteration of the ice surface albedo may be used to melt ice. Coal dust has been successfully used on the Chena River in Alaska and ordinary sediments may be of help on the Inland Waterways, if water quality regulations permit it.

b. Explosives. Explosives may be used to break up ice. This is useful only in specific instances of smaller ice problems and in areas not subject to damage from blasting.

c. Mechanical. Vessels may be used to break up ice. It does not appear that a vessel specifically designed for breaking ice on the Inland Waterways has been used recently. Some success has been enjoyed using air cushion vehicles.

Loss of Navigation Aids. Existing buoy markers can be knocked off station, damaged by ice action, or obscured during the winter. Maintaining existing buoys is difficult during the winter if heavy ice occurs.

Detrimental Weather Conditions. Snow, sleet and fog compound the existing difficulties of winter navigation. During extremely cold weather vapor coming off of the water causes a fog-like condition. To aid in averting collisions with other barges as well as bridges due to this condition, tows keep in radio contact with other tows in the area.

Ice Action on Bridge Piers. There is a possibility that part of the force required to break ice in the main navigation channel and access channels would be transmitted to bridge piers and other structures in the river. Such a force could cause damage to these facilities.

Access to Docks and Wharves. In general, traffic in the approach channels to most of the decks and wharves will be less frequent than in the main navigation channel. Because of this it is possible that ice will accumulate to a greater thickness in these approach channels because of ice displaced from the main channel, and navigation through this thicker ice may be more difficult and slower.

Coal Transfer Facilities

Coal loading and unloading docks are very similar in design, and only in one respect noted below is there a significant difference in these facilities. The most common design utilizes cylindrical piers called cells, constructed of concrete- or earth-filled sheet metal piling located along the terminal area. Their purpose is to prevent barges from grounding in the shallow water near shore, to guide barges under the coal loading or unloading equipment, and for tieing up barges awaiting loading or shipping. Cells range in diameter from about 6-20 ft and are on 150-200 ft centers (Fig. 27). Though the cylindrical design is the most common, single wood or steel piles or tripod piles are occasionally used by small terminals (Fig. 28). Floating ice is deflected from the dock cells by the use of two or three cells installed at the upstream end and normal to the dock alignment, projecting towards the channel. These are very effective in preventing damage to the dock, and no terminal operator contacted reported any damage from floating ice.

An unusual method to deflect ice from the shore uses a floating, wedge-prowed raft between two icebreaker cells (Fig. 29). Ice can still form or collect along the dock and may interfere with operations, however. A few terminals dispense with dock cells and substitute a concrete wall along which barges are spotted (Fig. 30). A winch-drawn cable, termed a running line, is generally used for drawing barges underneath the loading or unloading device. Harbor or switch boats are also used to spot the barges near the loading/unloading facility and transfer barges to the fleeting area. A few terminals use switch boats for pushing barges beneath the loading/unloading device.

Since harbor boats are used for moving at most a few barges at a time, they are not high powered, and generally range between 300 and 1000 hp. Terminals that do not have harbor boats depend upon the line carrier delivering the barges to fleet and spot both empty and loaded barges. Running lines cannot draw a loaded barge through heavy ice. In one terminal visited, the winch is torque-set for the load of one full barge, and 6-7 in. of ice prevents movement, so operations must depend upon the availability of a towboat to break the ice with its wheelwash, or to push the barge or barges through the ice cover.

Figure 27. Mooring cells forming an unloading dock, Ohio River.

Figure 28. Barges moored at small coal mine. Tripod cells used instead of cylindrical cells.

Figure 29. Floating wedge prowed raft added to two ice breaker cells on left. Ice is deflected into the main channel.

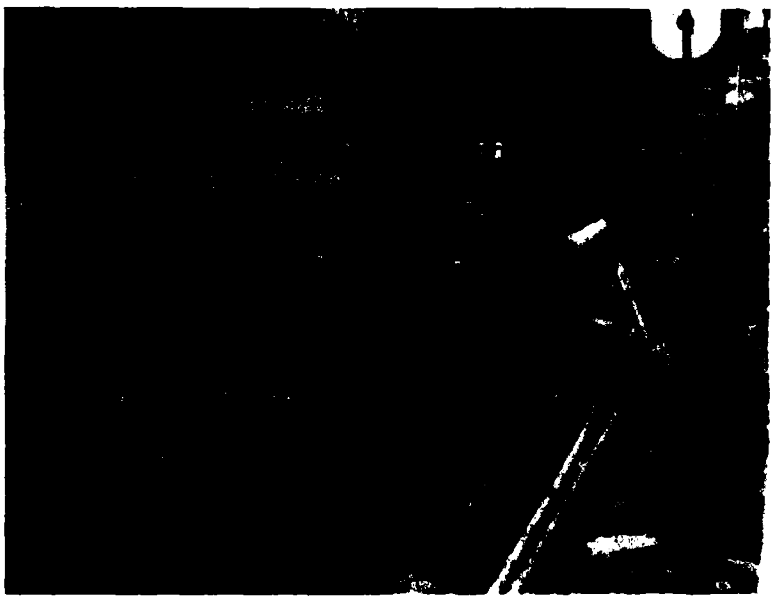

Figure 30. Stationary continuous bucket conveyor unloader, used without mooring cells, Allegheny River.

Loading docks use conveyors to feed coal into a chute fixed above the barge which is moored along the dock for loading (Fig. 31). Two passes are made with most barges to avoid large unbalanced loads (Fig. 32). The trend is to one-pass loading, but this requires a new design of barge which has reinforced members to withstand the large unbalanced loads.

Unloading facilities use either continuous bucket conveyor unloaders, Fig. 30, or clamshell buckets suspended from a whirling crane or a traveling crane. A terminal equipped with a continuous bucket unloader and receiving both jumbo and standard barges must have an unloader no wider than the box of the standard barge, and therefore two passes are necessary when unloading jumbos. Continuous bucket unloaders are pivoted at the top end of the conveyor to accommodate various heights of loads, but high water can place the barge too high for unloading, and operations cease until the water level drops (generally 1-2 days). No such constraint applies to the clamshell bucket unloader, although fast currents accompanying high water frequently result in the stoppage of operations. High water and high winds cause more delays and shutdowns than ice, except for exceptionally heavy ice years. Damage to docks caused by ice is negligible, but high water/high winds have occasionally driven barges against docks, damaging both the dock wall or cells and barges; in unusual cases barges have been sunk or swamped.

Frozen coal in barges can be off-loaded with no difficulty with either continuous bucket unloaders or clamshell buckets. However, large chunks of frozen coal can cause problems with the conveyor system: conveyors or storage hoppers become plugged, chunks fall off and damage equipment, and frozen coal thaws and slips on inclined conveyors (31). In fact, landside coal transfer problems cause more delays and costs in winter than river terminal operations. Brute force methods are used to break up large coal chunks, by men wielding pike poles or sledges. Utilities visited estimated more extra costs associated with landside coal transfer than river operations.

Rail/Barge Interface. The major problem associated with the railroad/barge interface is the freezing of coal in rail cars which can seriously delay off-loading at the tipple. "Stiffening" of the coal requires both low temperatures, long haul times from mine to terminal, and sufficient moisture coating the coal to act as a cement. Coal inherently contains water as mined, and it may have a high moisture content from washing at the mine, dust control practices, or a shipment may encounter rain or snowmelt during its transportation. Experience has shown that when the temperature drops to near 0°F, and residence time of the coal in the rail cars approaches five days, there is likely to be serious stiffening or freezing to the sides of the hopper. When that does occur unloading from either bottom-dumps with shakers or from rotary unloaders is hindered; brute force methods (rodding, banging car sides) have been used with varying success. A typical unloading time of 6 min is lengthened to 12-15 min when frozen coal is encountered. Two methods are used to avoid this

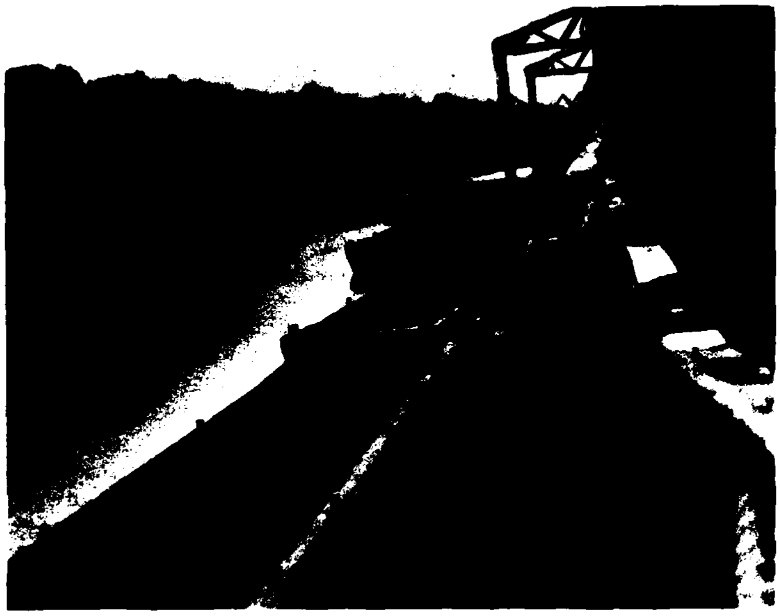

Figure 31. Coal loaded into barges through dual in-line chutes, Monogahela River.

Figure 32. Movable chute loading coal, starting second pass, Monongahela River.

problem: car heaters, and freeze-conditioning additives. In a typical car heating operation, the frozen coal car is moved into a shed where fuel-fired heaters direct a blast of hot air and exhaust gases on the sides of the car. This is obviously an expensive remedy and the coal usually drops out in 500-600 pound chunks.

Freeze conditioners are either glycol- or hydrocarbon-based materials sprayed on the coal at the time of loading at the mine. Hydrocarbon-based materials are favored for coking coal because they increase the bulk density of the coal going into the coking oven from 45 to 50 lb/ft^3, resulting in a stronger, less porous coke. Hydrocarbons are also less expensive than glycols, \$3.85 vs \$4.50-4.75 per gallon. Application rate varies from 1/2 to 2 pints per ton depending on the coal moisture content.

During the winter of 1979-80 some Ohio River barge companies strongly urged that all rail-hauled, small-sized coal to be loaded on barges be chemically treated. The coal is usually bottom dumped from the rail car onto conveyor belts into barges. Millions of tons have been so treated with greatly speeded up loading times.

The nature of the coal-ice bond is still not well understood and further study of the coal freezing problem is merited. This is particularly true since the possibility exists to save millions of dollars for ice bonding treatment as can be seen from the estimated costs in Table 12.

Table 12. Estimated Cost of Chemical Treatment of Coal.

	1975	1980	1990
Rail/Water Coal Movement (million tons)*	10	41	77
Chemical treatment (million gallons)**	.31	1.3	2.43
Cost (million 1975 dollars)	1.25	5.2	9.7

* Ref. (3).
** Assumes that one half of the coal has been treated at the maximum recommended level.

SURVEY OBSERVATIONS

The following details of ice problems were obtained by on-site visits to the different parts of the Inland Waterways.

The Monongahela and Allegheny Rivers

The Monongahela River is the second largest carrier of coal of the rivers studied with a number of major coal mines located on the river. Many users of coal, including utilities and steel plants, are also located on the river. Coal is the major commodity carried on the river, representing 82.5 percent of the total traffic during 1977. In general, problems on the Allegheny River are similar to those on the Monongahela. The Allegheny has little coal traffic; in fact, overall traffic on the river is much less than on the Monongahela River. No specific problems were identified on the Allegheny River.

Figure 33 is a map of the rivers showing the locks and dams on the rivers as well as the sites visited or contacted by phone. A key to the survey sites is provided in Table 13. Data on locks and dams are given in Tables 2 and 6.

Problems within the Navigation Channel. In the river channel a major problem occurs due to sheet ice. Very little traffic occurs on the upper Monongahela during the winter months. As a result the channel freezes solid with relatively thick ice making it difficult for tows to break through without risking extensive damage. Empty barges often ride up on the ice when ice breaking is attempted with them. Empty barges also tend to accumulate ice on their undersides during extreme cold periods. This causes clearance problems within the channel, as well as at lock sills and loading docks, after they have been loaded.

Problems at Locks and Dams. In addition to the usual problems caused by ice at locks, described earlier, two locks on the Monongahela River (Locks 7 and 8) are undersize for current and future needs. Ice conditions aggravate the problems caused by these locks. Each of these locks is only 56 x 360 feet while the remaining locks on the Monongahela are at least 84 x 600, some having two lock chambers.

Problems at Terminal Facilities. Many of the coal loading river terminals on the river operate without a switch boat. Therefore, all of the barges must be moved into position for loading and then moved downstream using winches and running lines. During ice conditions the barges will freeze in, particularly when left overnight, and the winches may be unable to move them. In other instances the barges will ride up on the ice when empty. When this happens a passing boat must be called into the terminal area to break up the ice and flush it out into the channel. If no tow boats are passing by one must be brought in from the nearest source or loading temporarily stopped. Another problem occurring at terminals is the accumulation of ice between the barges and the cells to which the barges are moored. Some loading/unloading facilities have fixed chutes/buckets and the accumulated ice forces the barge beyond the limits of operation. In other instances loading/unloading areas may have cells on either side with little room for clearance remaining when a barge is

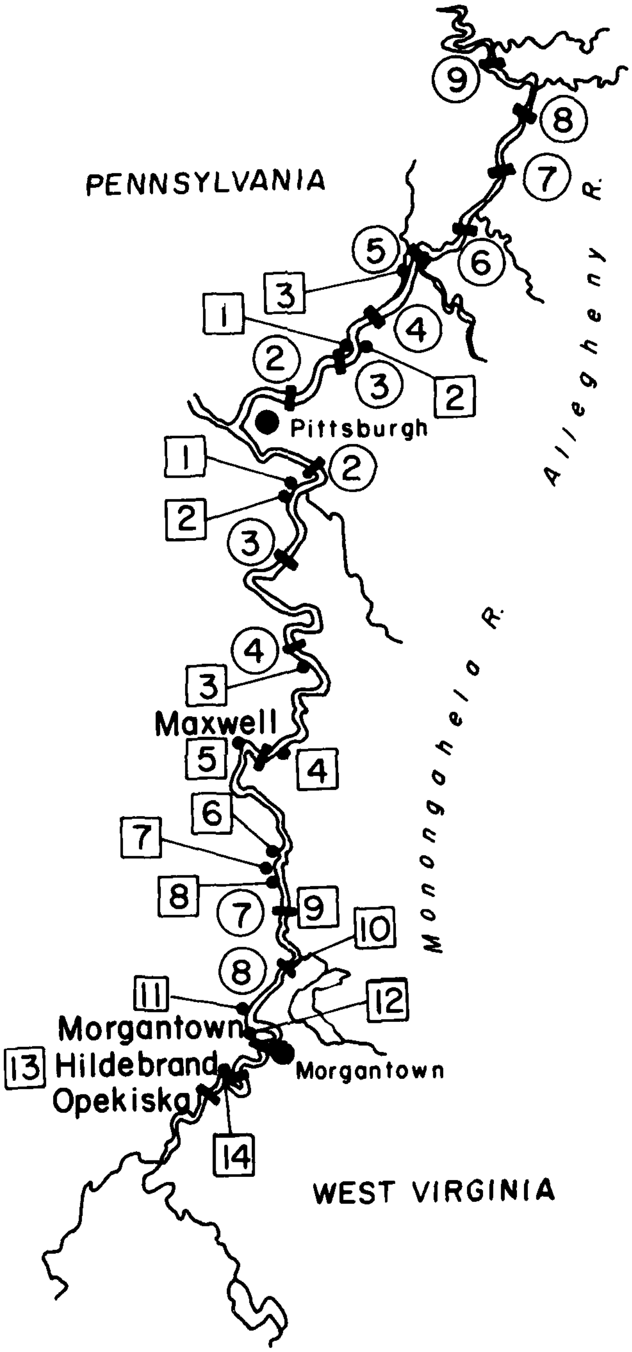

Figure 33. Sites surveyed on the Monongahela and Allegheny Rivers. Circled numbers are dam designations; boxed numbers are sites visited and are keyed to Table 13.

Table 13. Sites Surveyed on the Monongahela and Allegheny Rivers.

Site No.	River mile and bank side	Site visit (V) or telephone interview (T)	Facility	Location
		Monongahela River		
1	17L	V	Ohio Barge Line	Dravosburg, PA
2	18.6-21.1L	V	U.S. Steel, Clairton Works	Clairton, PA
3	43.5L	V	Mon River Towing	Belle Vernon, PA
4	57.8R	V	Hillman Barge & Construction Co.	Brownsville, PA
5	62.6L	V	U.S. Steel, Karen Mine	Vestaburg, PA
6	79L	V	Hatfield's Ferry Power Plant, West Penn Power Co.	Masonville, PA
7	80.3L	V	U.S. Steel, Robena Mine	Grays Landing, PA
8	81.2L	V	U.S. Steel, Cumberland Mine	Grays Landing, PA
9	85.0	V	Lock and Dam No. 7	Greensboro, PA
10	90.8	V	Lock and Dam No. 8	Point Marion, PA
11	96.7L	V	Consolidation Coal Co., Humphrey Mine	Star City, PA
12	98.1L	V	Consolidation Coal Co., Arkwright mine	Star City, PA
13	114.3L	V	Christopher Coal Co.	
		Allegheny River		
1	15.3R	V	Cheswick Power Plant, Duquesne Light Co.	Cheswick, PA
2	18.6L	T	Standard Terminals	New Kensington, PA
3	29.5R	V	Freeport Terminals	Freeport, PA

between them. This can make it difficult if not impossible to move a barge into a position for loading/unloading and may make it difficult to move the barge out of position.

The major barriers to increased coal flow on the Monongahela are locks 7 and 8. Ice conditions serve to aggravate the capacity limitations of these facilities. With the demand of the coal liquifaction facility at Morgantown, WV added to an increased coal flow on the Monongahela both upbound and downbound, these undersize locks will become serious bottlenecks.

Problems at the terminal facilities are not insurmountable. Increased traffic and terminal activities along with the replacement of outdated facilities will help solve the problems in these areas.

Ohio River and Tributaries

The upper part of the Ohio has characteristics similar to the Monongahela and Allegheny Rivers, which join to form it at Pittsburgh. It is relatively narrow with many dams which create quiescent upper pools and swift flow immediately downstream from a dam. The middle Ohio is considerably broader and in its lower reach from lock 53 to Cairo, IL, it is an open river. Fig. 34 shows the Ohio River with a key to the sites visited given by Table 14. Data on the locks and dams are given in Table 1.

Ice is principally found in the upper Ohio, supplied by the Allegheny and Monongahela Rivers. Ice may be discharged in relatively small amounts frequently during the winter as tows break up the ice cover, but it is mainly following heavy rains or the Spring break-up that large quantities of ice move down the river. Passage of ice in these surges takes not more than two days normally, during which some operations such as fleeting or midstream running may be postponed. Terminal operations are seldom curtailed because of ice.

Only one coal unloading operation, of those contacted, reported any serious delay due to ice: the W.H. Sammis plant of Ohio Edison, located at mile 53 about one mile above New Cumberland Locks and Dam. The plant has two dock areas, the north site with 18 cells for fleeting, and the south site with 17 cells for unloading operations by a continuous bucket conveyor and a clamshell bucket. Each site has ice breaker cells at the upstream end. Even in relatively open winters floating ice collects along the dock because of the river current - possibly influenced by New Cumberland Dam - and delays unloading operations. Ice closed the entire unloading facility for a month in January 1978. The 650-hp harbor boat used for barge spotting was unable to cope with the ice, and a 7500-hp towboat brought in from a line hauler was unable to break enough ice to operate the barge spotting running line. However, no damage has been suffered by the terminal as a result of ice. In early January, 1981, the terminal was beginning to slow down unloading operations as ice collected at the dock,

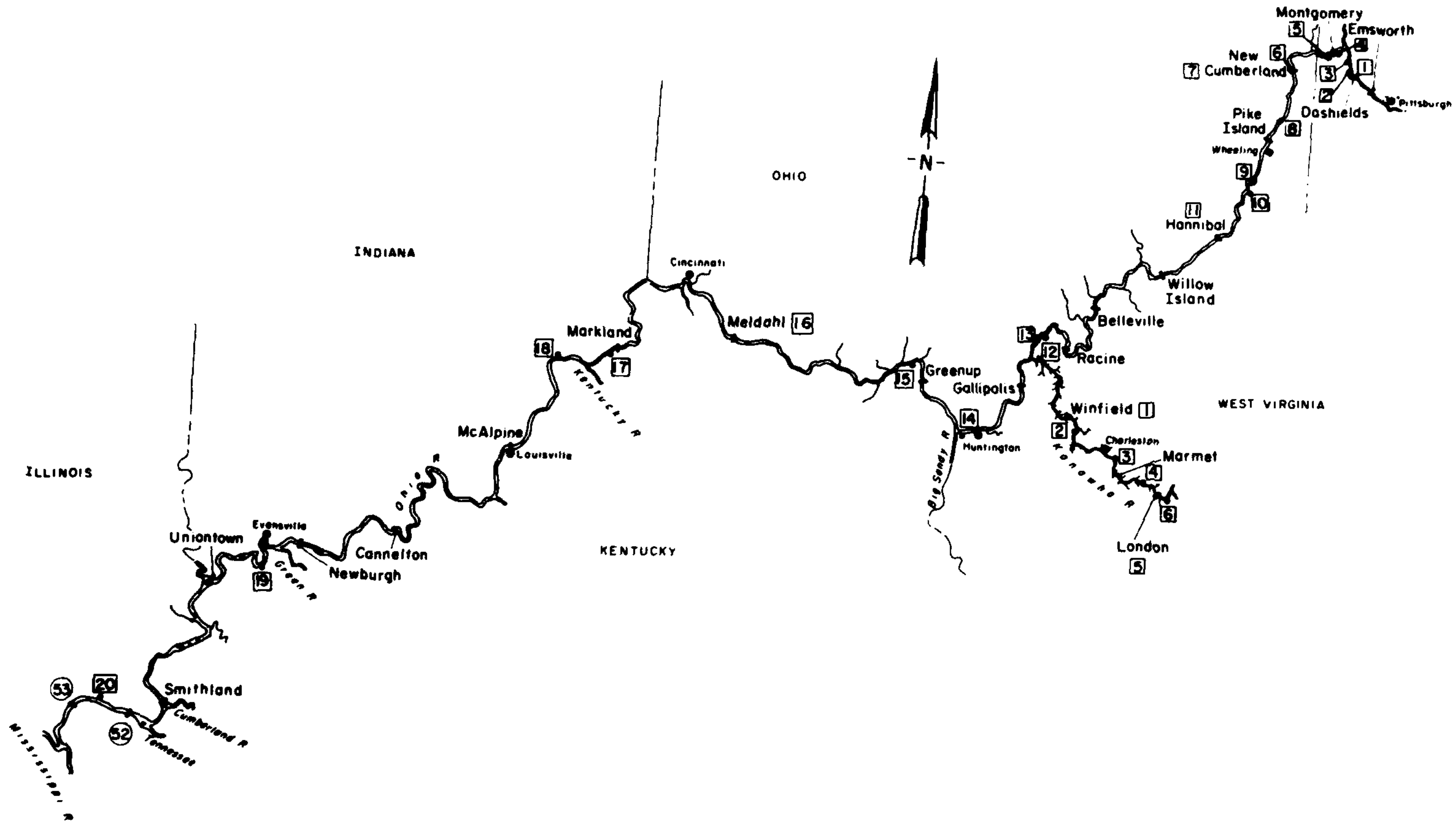

Figure 34. Sites surveyed on the Ohio and Kanawha Rivers; boxed numbers are keyed to Table 14.

Table 14. Sites Surveyed on the Ohio and Kanawha Rivers.

Site No.	River mile and bank side	Site visit (V) or telephone interview (T)	Facility	Location
			Ohio River	
1	15.2L	V	Frank R. Phillips Power Station, Duquesne Light Co.	Wireton, PA
2	15.9L	T	North Star Coal Co.	South Heights, PA
3	18L	V	Jones & Laughlin Steel Corp., Aliquippa Works	Aliquippa, PA
4	29.8L	V	ARCO Polymers, Beaver Valley Plant	Monaca, PA
5	33-34L	V	Bruce Mansfield Power Station, Pennsylvania Power Co.	Shippingport, PA
6	53R	V	W.H. Sammis Power Station, Ohio Edison Co.	Port Homer, OH
7	54.4	V	New Cumberland Lock and Dam	Stratton, OH
8	76.7R	V	Cardinal Power Station, Ohio Power Co.	Brilliant, OH
9	101.8R	V	Burger Power Station, Ohio Edison Co.	Dille Bottom, OH
10	112.1-112.5L	V	Mitchell, Kammer Power Stations, Ohio Power Co.	Captina, WV
11	126.4	V	Hannibal Lock and Dam	Hannibal, OH
12	257L	V	Indiana-Michigan Electric Co., River Transportation Div.	Lakin, WV
13	258R	V	Gen. James M. Gavin Power Station, Ohio Power Co.	Cheshire, OH
14	316.8L	V	Ohio River Co., Kenova Terminal	Kenova, WV
15	351L	T	Kentucky-Ohio Transportation Co.	South Shore, KY

Table 14. (Continued)

Site No.	River mile and bank side	Site visit (V) or telephone interview (T)	Facility	Location
16	436.2	V	Cpt Anthony Meldahl	Foster, KY
17	535.2L	V	Clean Coal Terminal	Ghent, KY
18	560R	T	Clifty Creek Power Station, Indiana-Kentucky Power Corp.	Madison, IN
19	807.8L	T	The Riverport, Henderson County Port Authority	Henderson, KY
20	952.3	T	Electric Energy, Inc.	Joppa, IL
		Kanawha River		
1	31.1	V	Winfield Lock and Dam	Eleanor, WV
2	39.2L	T	Putnam Coal Terminal, Appalachian Power Co.	St. Albans, WV
3	64R	V	Amherst Industries	Port Amherst, WV
4	78.3R	T	Kanawha River Power Plant, Appalachian Power Co.	Glasgow, WV
5	82.8	V	London Lock and Dam	London, WV
6	87.5L	V	Hawks Nest Mining Co.	Eagle, WV

and plant personnel estimated that another several days of very cold weather would have shut down the operation. A sudden rise in temperature followed by heavy rains ended any such threat. In general, if a river channel can be kept open, shore terminals can be operated with little or no delays.

The winter of 1977-78 caused extreme ice conditions over much of the Ohio River. Though ice in the upper Ohio was not severe enough to stop operations, with the exception described above, the ice jam at Markland Dam and the closure of the locks there, and a jam near Carrsville, KY, prevented traffic from moving past those points. Long haul traffic was curtailed but short-haul traffic was able to continue. River blockages serve to demonstrate how greatly the Ohio River basin economy is based upon steady river traffic: shortages of fuel, chrome ore, deicing chemicals, and other commodities were felt shortly after navigation stopped.

Ice problems occur infrequently on the Kanawha. The extremely severe winter of 1977-78 resulted in ice forming bank to bank above London Dam, and all river operations closed for 20 days when tows were unable to break through the reported 6-in. ice. In a normal year the occasional floating ice causes no interference to operations above Winfield Dam. The incidence of ice increases below Winfield, a distance of 31 miles from the confluence with the Ohio, but operations are not significantly affected. According to one barge operator, ice does not build up on the bottom of barges in the Kanawha.

Mississippi River and Tributaries

Traffic on the Mississippi is significantly reduced during the winter between the mouth of the Illinois Waterway and points north, although towboats can navigate to Burlington, Iowa. The shippers rule of thumb dictates departing St. Paul southbound by Thanksgiving, since continuous ice begins to form in early December. Fig. 35 is a map of the river section and Table 15 is a key to the sites surveyed. Data on the locks and dams are given in Table 3. The worst reach of the Mississippi that remains open in winter lies between St. Louis and Cairo. Extremely heavy ice conditions were experienced during two consecutive winters, 1976-77,1977-78. In the first winter, a 100-mile long ice gorge closed the river for 27 days. Industry attempts to break through the ice using towboats as ice breakers were unsuccessful until the gorge began breaking up when temperatures moderated. Ice sufficiently heavy to affect shipping usually occurs from early January until mid February.

Sand bars very commonly form along river bends. Floating ice then becomes grounded in the shallow water and serves to intercept more floating ice, with the result that ice encroaches into the navigation channel.

The Kaskaskia River flows into the Mississippi at mile 117.5 above Cairo. It is navigable for only 32 miles, but ice does cause delays at the

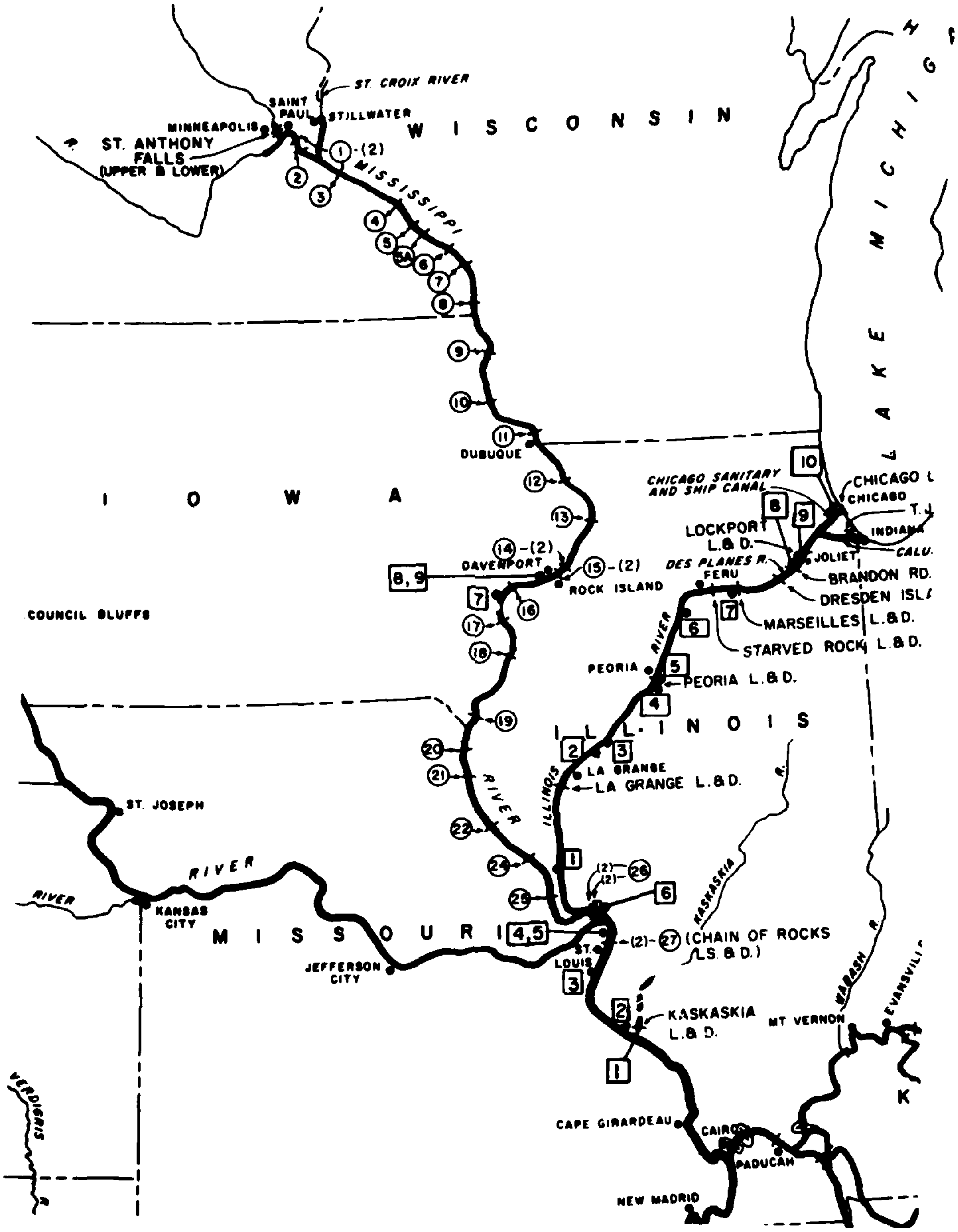

Figure 35. Sites surveyed on the Upper Mississippi River and Illinois Waterway (boxed numbers; see key in Tables 15 and 16).

Table 15. Sites Surveyed on the Mississippi River

Site No.	River mile and bank side	Site visit (V) or telephone interview (T)	Facility	Location
1	117.5	T	Kaskaskia Lock and Dam	Chester, IL
2	125.6L	T	Consolidation Coal Co., Kellog Dock	Modoc, IL
3	161.4R	T	Meramec Generating Station, Union Electric Co.	St. Louis, MO
4	184.7R	V	American Commercial Terminals, Inc.	St. Louis, MO
5	185.7	V	Tri-City Regional Port District	Granite City, IL
6	203	V	Lock and Dam No. 26	Alton, IL
7	453.0R	T	Muscatine Power and Water Co.	Muscatine, IA
8	481	V	Iowa-Illinois Gas and Electric Co.	Davenport, IA
9	483.3R	V	Alter Barge Line	Davenport, IA

Kaskaskia lock at mile 0.8 above the Mississippi, and occasionally upriver.

The Illinois Waterway

Coal represented 16% of the total cargo on the Illinois Waterway in 1977. Most of the coal traffic on the river is upbound and a major portion originates on the lower part of the river. Utilities are the primary users of coal on the river. Figure 35 is a map of the river showing the 8 locks and dams on the river as well as the survey sites. A key is provided in Table 16 for the survey sites. Data on the locks and dams are given in Table 4.

Problems within the Navigation Channel. During periods of extreme cold, which occur nearly every winter in this region, ice conditions become very bad on the Illinois Waterway. In these instances all traffic is stopped for periods up to 60 days. Nearly every year traffic is stopped completely for a period of 3 to 4 weeks. For this and other reasons the utilities affected must stockpile approximately a 90 day supply of coal. Some of the power plants are also served by rail, but others rely completely on water. During the winter of 1978-79 one utility went 104 days without any coal deliveries due to ice and high water. Power production at this plant had to be restricted and finally one generating unit shut down due to low coal reserves.

Problems at Locks and Dams. Problems due to ice at locks and dams on the Illinois Waterway are most acute at Peoria Lock and Dam. Traffic conditions through this lock are very heavy during its entire operational season. On the average, 3 million tons of cargo per month pass through this lock with traffic slightly heavier during the winter. Above Peoria Lock and Dam, the Illinois River is very wide forming what is called Peoria Lake. Ice forms very rapidly on this shallow section of the river. Because of the extremely heavy traffic, delays in locking due to ice conditions cause long waiting times at the lock. Allowable tow size in the lock is also reduced to allow room for floating ice. During extreme ice conditions two ice lockages are necessary before the tow can enter the lock chamber. Even during a relatively mild winter such as 1980-81, over 30 tows were waiting for lockage at Peoria lock for periods up to 3 to 4 days.

Problems with Barges and Towboats. Because of extreme ice conditions on the Illinois Waterway, nearly every year carriers stop operations for some portion of winter. The risk of ice causing extensive damage to their barges and towboats coupled with reduction in tow size and other increased costs make it uneconomical for them to operate during this period. As mentioned earlier this period averages 3 to 4 weeks per year with extreme cases being 2 months or more. High water which follows in the Spring has also stopped operations for 30 days or more.

Problems at Terminal Facilities. Most of the terminal facilities on the Illinois Waterway are utility owned. In most instances thermal waste

Table 16. Illinois Waterway Survey Sites.

Site No.	River mile above mouth	Bank right (R) left (L)	Site visit (V) or telephone interview (T)	Facility owner or operator	Location
1	42.7	R	T	Western Illinois Power Coop	Pearl, IL
2	118.5	L	T	Illinois Power Corp.	Havana, IL
3	120.8	L	T	Canal Barge Co.	Havana, IL
4	157.7	L	V	Peoria Lock and Dam	Pekin, IL
5	158.0	L	V	Central Illinois Dock Co.	Pekin, IL
6	212.0	L	V	Illinois Power Co.	Hennepin, IL
7	239.5	L	T	LaSalle-Peru-Ottawa Terminal	Ottawa, IL
8	285.5	R	V	Brandon Road Lock and Dam	Joliet, IL
9	295.7	R	T	Commonwealth Edison Co.	Romeo, IL
10	318.8	R	T	Commonwealth Edison Co.	Chicago, IL

from the power generation process is being discharged to the river. Discharges are usually in the area of the terminal facilities and thus tend to suppress the formation of ice at these facilities. Ice is seldom a problem at these terminals with the exception being periods of extended extreme cold. Most of the terminal facilities on the Illinois Waterway maintain their own switch boat. This also greatly reduces the impact of ice on operations. No major damage due to ice was reported at any of the facilities surveyed.

The major constraint on increased coal flow on the Illinois Waterway is Peoria Lock and Dam. Other locks and dams along the river also represent bottlenecks to a lesser extent. Additional lock chambers of 110 x 1200 feet have been proposed for each of the locks on the Illinois Waterway with the exception of the T.J. O'Brien lock at Chicago. The addition of air bubbler screens would probably help the situation at Peoria Lock and Dam during the winter months. Since traffic is very heavy year round, the proposed additional lock chambers also appear to be warranted. With these improvements, the lock and dam barriers to increased coal flow would be removed.

Another barrier to increased coal flow on the Illinois Waterway is the ice conditions which cause shut down nearly every year. Ice breaking might help this situation to some extent. Floating ice becomes a major problem since it can and does damage the screws (propellers) of tow boats. Effective ice management could alleviate some of this problem.

COST PENALTIES OF WINTER OPERATIONS

The cost of operating a 5000 hp towboat is about $6,000 per day and for a 10,000 hp towboat about $10,000 per day. Thus delays due to ice can be a significant economic burden. Compounding the increased cost is the productivity loss when tows must be reduced in size in order to negotiate ice. A 15 barge tow of jumbos represents a capacity of 21,000 tons of coal (equivalent to more than two unit trains of 100 cars, each holding 100 tons); unit shipping costs will obviously increase if the tow must be reduced.

Damage to barges operating in ice-infested waters is very common. Denting of the skin or deformation of the frames may be of no immediate consequence but can cause structural weakening and contribute to later, more serious problems. Holing of barges by ice is common; temporary repairs consisting of welding a patch, using bilge pumps to handle slow leaks, or a wooden plug in the hole may suffice until more permanent repairs can be made. Damage to towboats can be of greater consequence: one operator has reported that a single boat has suffered as much as $25,000 damage to screws and hull in a heavy ice year. Another operator reported a loss of $45,000 in a single incident. Ice often damages screws

at a replacement cost of $15,000 to $25,000 each. To avoid exposure to ice and potential ice damage, many operators curtail operations in winter.

Cold weather affects worker productivity by reducing the time of outdoor exposure and by lengthening the time for accomplishing many tasks. One operator stated that the normal time of 5 hours required for making up a 15-barge tow may increase to 24 hours during ice conditions. There are occasions when crews have to crawl on ice-sheathed barges in order to handle lines. Continuous operation during the winter may require the addition of two deckhands to the normal six (normal full crew on a line boat consists of 11 men) on a tow. Receiving terminal crews generally are not augmented except in cases where ice has delayed receipt of coal and a sudden influx of many barges requires extra shifts or extra men. Occasionally additional workers are needed to handle coal at the receiving stations when coal freezes in chunks and will not move on conveyors, etc.

Because ice often stops the flow of coal, most users stockpile coal to cover these periods. (Stockpiles are also needed to cover other interruptions in supply such as labor strikes.) Oxidation of stockpiled coal reduces its heating value. In addition the costs of reclaiming coal from a stockpile as opposed to bringing it directly from the barges into the plant are often significantly higher. One utility reported an increase in handling costs of 165% for reclaiming stockpiled coal as opposed to bringing it directly from barges on the river.

Fuel consumption is increased in pushing a tow through ice. Interestingly, the same energy is required to break through a continuous ice cover as to push through broken (brash) ice, as demonstrated in tests conducted by CRREL on the Mississippi River (Ashton et al. (6)). Energy is dissipated by the friction of ice scraping the sides of the barges, and by the ice displaced underneath which also adds to frictional loss. It is also possible that the energy absorbed by the front barges riding up on a continuous ice cover and causing failure in the ice by bending is equivalent to the energy required to displace brash ice or to push along an "ice prow" of brash ice.

Though some damage results to locks due to ice forces, both to lock walls and miter gates, no cost figure is available since all maintenance costs are grouped together. The figure is not considered high, however.

Increased erosion of the shoreline due to ship passages through ice has been reported. A figure of $738,000 was quoted by the St. Louis District for one year repair costs on the Illinois Waterway and Mississippi River. This figure will be reduced by using 500 lb top size riprap (crushed rock) along the shore.

CONSTRAINTS ON SYSTEM CAPACITY

Bottlenecks presently occurring at some locks which are inadequate to handle summertime traffic will be exacerbated if wintertime traffic in the presence of ice approaches summer levels. The period between late December and late February is generally the time when ice forms sufficiently to affect operations on open rivers. For one-sixth of the year, therefore, there will be a high probability of increased delays because of ice affecting locking operations. Ice forming at terminals and docks is not presently a signficant factor in causing delays or affecting operations more than transiently. Extra cost is incurred because of the need to break ice along the dock when it does form, however.

A system analysis of the entire United States transportation network indicated that a slower growth of Appalachian coal would lead to a reduced growth rate of barge traffic, although tonnages would still increase (3). Future domestic water movement of coal did not appear to have significant capacity constraints with the exception of certain locks. The Gallipolis Lock on the Ohio River must be upgraded, as well as Lock 26 on the Mississippi River. These projects have already been approved and these bottlenecks should be removed by 1990. Obsolete lock structures on the Monongahela River near Pittsburgh must be upgraded to at least the 84 x 600 ft standard. In general the system would be well served if all locks on the major rivers and some tributaries were upgraded to 1200 ft length. By 1990 the Cumberland and Tennessee Rivers will play a much greater role with coal moving up these rivers and the Ohio River to Ohio and Pennsylvania, a flow reversal from the present one.

CONCLUSIONS AND RECOMMENDATIONS

Based upon the field surveys and published reports, the ice constraints on the expansion of coal movement on the Inland Waterways, in order of importance, are:

1. Navigation channels
2. Locks and dams
3. Coal handling facilities

The coal loading and unloading terminals do not have any inherent problems related to ice, which would hamper an increased coal movement on the river systems. Only rarely does an incident occur where coal movement is interrupted due to ice problems at the handling facility when the navigation channel or locks are not shut down. Under most winter conditions the operators are able to load and unload without interruption even when shipping is slowed or stopped due to ice in the channels or at locks. The coal handling equipment is sometimes idled due to minor mechanical problems, unrelated to ice, and the system is being used at

considerably below capacity. Numerous terminals, which have operated in the past, are now idle and can be brought back into service if necessary. It seems likely that increased traffic will be beneficial for some present, although minor, ice problems. Clearing the dock approach and freezing of stationary barges will be lesser problems if traffic increases. The major problem for the coal handling systems (although this is at present not a serious impediment to coal movement) is freezing of the small sized coal in train cars and in barges. The coal frozen in barges can be removed easily but the large frozen chunks sometimes cause problems for conveyor systems. The coal frozen in unit trains is more serious, and the 1990 projections of coal flow indicate that western coal will move up the Ohio River. This means that there will be an increased transfer of coal from train cars to barges. Thus the frozen coal in train cars could slow the loading of coal into barges. Methods to deal with this problem have been described in the report but further research is advisable.

For the time span up to 1990 the only serious problems of winter transport of coal will be those associated with the locks and dams and the navigation channel. Further research and development will be needed to find the most cost and energy effective ways to minimize these ice problems. The following areas of ice research require further study.

A. Effect of navigation on ice in the navigation channel.

B. Prevention of ice formation in the navigation channel.

C. Removal or storage of channel ice.

D. Application of energy for the control of ice at locks and dams.

E. Lock and dam design modifications to allow full operation with ice present.

F. Freezing of coal in train cars and the transfer of coal from train cars to barges.

G. System study of the effect of winter navigation on coal storage requirements along the Inland Waterways.

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APPENDIX: GLOSSARY

Double locking. A tow which is too long to fit within a lock is broken into sections that will fit, and the separate sections locked through using cable pulls for the first sections and the towboat for pushing through the final section.

Double tripping. Similar to double locking but differs in that the towboat pushes each section through the lock; used at those locks which have no winching capability.

Fixed crest dam. A dam whose main damming surface is fixed at some height above the stream bed and over which surplus water flows.

Gorge. A solid mass of broken ice which dams the river and can stop navigation.

Ice jam. An accumulation of ice which, in a river, restricts the flow of water causing an abnormal head differential.

Jumbo barge. An open-top cargo-carrying floating box with overall dimensions of 195 ft. long and 35 ft. wide; it can normally carry 1450 tons of coal in a 9 ft. deep navigation channel.

Lock. A navigation structure which allows a vessel to pass from one water level to the other at a dam.

Movable crest dam. A dam whose main damming surface can be raised out of the water or lowered towards the stream bed to pass surplus water.

Mule training. An operating procedure whereby a towboat pushes a single barge and tows the remainder of his barge string with limber lines.

Navigation dam. A structure built across a river to control channel depths, reduce current and level fluctuations, and create stable pools for terminal facilities. It is almost always associated with locks.

Semi (barge). Jargon for a semi-integrated barge, one that has a raked bow and a box stern.

Standard barge. An open-top cargo-carrying floating box with overall dimensions of 175 ft. long and 26 ft. wide; it can normally carry 950 tons of coal in a 9 ft. deep navigation channel.

Stumbo barge. A hydrid of the jumbo and standard barges, with dimensions of 195 ft. long by 26 ft. wide.

Two-boat tows. The practice of operating a towboat backwards at the head of a tow to use its wheelwash for breaking and deflecting heavy ice, the tow being pushed by another towboat.

Wheelwash. Turbulence created by a tow boat propeller, used to break or push aside ice or other debris.

Wicket dam. A dam with movable gates, in the form of shutters, attached with a frame to the stream bed. The wicket gate can be lowered during high water with no overhead obstacle to navigation. It is classifed as a navigable, movable, dam.

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